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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TCREC TECHNICAL REPORT 62-36

HOVERING STATIC STABILITY
AND PERFORMANCE EXPERIMENTS
ON THREE-DIMENSIONAL ANNULAR JET MODELS

Task 9R99-01-005-02

Contract DA 44-177-TC-709

November 1961

prepared by:

AERONUTRONIC
A Division of *Ford Motor Company*
Ford Road,
Newport Beach, California

DISCLAIMER NOTICE

ASTIA AVAILABILITY NOTICE

The contemplated Army missions for Ground Effect Machines require that
the ground clearances be greater and the overall machine dimensions be
smaller, leading to a higher value of h/d ratio than has usually been
investigated for air cushion concepts. Since the annular jet and plenum
chamber configurations normally become unstable at h/d ratios above 0.05
to 0.1, this investigation was undertaken to determine the static stability
of a generalized annular jet in hovering and forward flight and to evaluate
various modifications which would improve the stability. In addition to
stability, data were generated on control forces and performance.

The results of this investigation indicate that inherent stability can
be achieved in the GEM at the operating heights believed to be necessary
for overland use.

FOR THE COMMANDER:

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SPECIAL PROGRAMS OPERATIONS

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TECHNICAL REPORT

HOVERING STATIC STABILITY AND PERFORMANCE EXPERIMENTS ON THREE-DIMENSIONAL ANNULAR JET MODELS

Prepared by: Approved by:

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

3

LIST OF SYMBOLS

Symbol	Description	Units
b	Characteristic model length (base + jets)	ft
C_m	Pitching moment coefficient = $M/L \cdot b$	--
C_l	Rolling moment coefficient = $1/L \cdot w$	--
C. P.	Center of pressure in % b or w	%
C. G.	Center of gravity (moment center in % b or w)	%
d	Effective diameter = $\sqrt{4S/\pi}$	ft
G	Ground effect power factor (see Page 81)	--
h	Height (base to ground)	ft
HP	Jet horsepower = $P/550$	HP
l	Jet peripheral length (on jet centerline)	ft
l	Rolling moment	ft lb
L	Lift force (perpendicular to ground)	lbs
M	Pitching moment	ft lb
P_b	Static pressure under base	lbs/ft^2
P_j	Static pressure in jet	lbs/ft^2
P_{t_j}	Total pressure in jet	lbs/ft^2
P	Jet power = $Q \cdot \bar{P}_{t_j}$	ft lbs/sec
Q	Jet flow quantity = $\int_o^1 V_j t \, dl$	ft^3/sec
q_j	Jet dynamic pressure = $\frac{\rho}{2} V_j^2$	lbs/ft^2

4

Symbol	Description	Units
S	Reference area (base + jet)	ft^2
S_b	Base area	ft^2
S_j	Jet area	ft^2
t	Jet thickness (perpendicular to jet)	ft
V_j	Jet velocity = $\sqrt{2\,q_j/\rho}$	ft/sec
w	Characteristic width (base + jet)	ft

SIGN CONVENTION

M	Positive if in direction of initial rotation. Negative if in opposition to initial rotation.
l	Same as above.
L	Positive up.

5

SUMMARY

Hovering static stability and performance experiments have been conducted with a series of three-dimensional annular jet models. The model planforms measured 40 by 20 inches and incorporated one-inch thick jets operated at a total pressure of 41.5 pounds per square foot. Height-length ratios of 0.05 to 0.20 were investigated.

Simple vertical and 45° inclined peripheral jets demonstrated static longitudinal stability at low heights and instability at high heights. The crossover point was h/b = 0.075 for the vertical jet and h/b = 0.107 for the 45° inclined jet. Static lateral instability existed for both models at all heights.

Convex and concave base shaping with a depth equal to 5% of the model length did not appreciably affect stability in either pitch or roll.

A rigid skirt together with rigid base segmenting flaps of length equal to 5% of the model length were effective in augmenting longitudinal and lateral stability when they extended two-thirds the way to the ground, but were not very effective when they extended only half way to the ground. The order of increasing effectiveness of segmenting flap configuration was, concentric, corner lobe, and centerline.

The concentric, corner lobe, and centerline jet segmented configurations were all statically stable in pitch at all heights including 20% of the length. The order given is in order of increasing stability. In roll, the first two configurations were stable at heights up to 20% of the model width, while the centerline jet segmented model was stable at all heights including 40% of the width.

All comments on stability apply to tilt angles equal to or less than one-third of the touchdown angle. At angles approaching touchdown even the centerline jet segmented model becomes unstable.

The configurations investigated were not optimized for hovering performance. The configurations are, however, representative of compromises which occur due to forward flight considerations. For these cases, the penalty in hovering performance due to jet segmentation was only 8% at height/length = 0.10 and only 4% at height/length = 0.20 for the corner lobe and centerline jet configurations. The concentric jet configuration actually had an improvement of 8% and 11.5% respectively at the same heights.

INTRODUCTION

Contract DA 44-177-TC-709 undertaken by Aeronutronic for
U. S. Army Transportation Research Command called for study
of stability and control of air-cushion vehicles for overland use.
The scope of the study was restricted to <u>static</u> stability and
control investigation, and emphasized the realm of height-diameter
ratios near and beyond 0. 10.

The work was divided into three phases. Phase I consisted of
hovering studies and experiments. Phase II covered the design
and preparation of a wind tunnel model and program based on the
information generated in Phase I. Phase III consisted of Test and
Analysis of the wind tunnel model.

The results of Phase I are reported herein. This report is confined
to stability data as outlined in the proposal (Reference 2). Extensive
control investigations were conducted on the hovering rig in the
same time period as part of an Aeronutronic funded program, and
will be reported separately as a portion of Contract DA 44-177-TC-
745.

Information from Phase II was forwarded on June 27, 1961 (Ref-
erence 3) in the form of a pre-test memorandum. The final report
covering Phase III is submitted as Aeronutronic Publication No. U-1447
(Reference 4), together with the subject report.

TEST FACILITY

The general arrangement of the Aeronutronic hovering test
facility is illustrated by the photograph presented as Figure 1.
Flow was supplied by a Chicago Airfoil Centrifugal Blower
driven by a 30-HP, 3-phase electric motor through belts and
pulleys. This unit was mounted at the top of an 11-foot tower.
Figure 2 presents an envelope of maximum pressure and flow
combinations available from the unit. Lines of actual flow versus
supply pressure are also presented for the five different jet con-
figuration models. The experiments were conducted at a constant
jet total pressure level of 41.5 pounds per square foot.

An 8-foot by 8-foot ground board was supported on a central
jack post which permitted height adjustment. The board was
mounted to the jack with trunions which permitted rotation of the
ground plane in pitch or roll. The ground board was locked into
position by posts at four corners which were C clamped to the
tower as shown in Figure 1.

9

MODEL AND INSTRUMENTATION DESCRIPTION

All models in these experiments were bolted rigidly to the bottom
of the long vertical duct. All force data was obtained through
integration of pressure distributions picked up from the model
base and jets. Various models are depicted in the photograph
included as Figure 3. The central model presents a base view
of the 45° model and includes the outer nozzle wall as well as
the base. The remaining models in the photograph present a top
view of several base inserts which fit concentrically within the outer
nozzle wall of the basic vertical jet model. Three examples of jet
segmentation are included together with a basic unsegmented base.

Figures 4 through 10 provide geometric description and instru-
mentation locations for the following models:

Vertical Peripheral Jet	Centerline Jet Segmented
45° Inclined Peripheral Jet	Corner Lobe Jet Segmented
Shaped Base	Concentric Jet Segmented
Skirted and Flap Segmented	

The static pickups indicated by 0 on the above drawings consisted
of .065" O. D. .012" wall stainless steel tube mounted at right
angles to and flush with the surface. The total head tubes indicated
by X on the above drawings were made from the same tubing and
mounted in the center of the jet. The mouth was located one-half
inch above the bend in the tube. All tubes were gathered together
in one spot just under the base top, routed vertically up the duct
through a hollow tube, and then horizontally out of the duct through
a hollow streamlined strut. The pressures were conducted by
plastic tubing to the 50-tube water manometer shown in the back-
ground of Figure 1 and photographically recorded.

DATA REDUCTION PROCEDURES

Each base static pressure tap was assumed to have an area of influence and to be located at the centroid of that area of influence. The base lift was obtained by summing the pressure-area products. The arms from the pressure tap to the pitch axis and roll axis were recorded. The net moments were obtained by summing the pressure-area-arm products.

Each instrumented jet location had an inner wall static tap, an outer wall static tap, and a mid jet total head tube. The two wall tap values were averaged to get the effective static pressure p_j - this was subtracted from the total head p_t; to get the local dynamic pressure q_j. The local reaction pressure was computed = $p_j + 2 q_j$ The jet lift was obtained by summing the reaction pressure-area products. The lift of the 45° jet which was summated along the jet was multiplied by .707 to get the component perpendicular to the base. The jet moment contributions were obtained by summing the reaction pressure-area-arm products. The arms were measured as the perpendicular distance between the jet centerline and the centroid of the model planform in the plane of the base.

The total lift was found by multiplying the sum of the base lift, and the jet component perpendicular to the base by the cosine of the tilt angle. This is wind axis or lift perpendicular to the ground.

The jet velocity in ft/sec was obtained from the dynamic pressure at each jet instrumented location. The volume flow in ft^3/sec was found by summing the velocity-jet area products. The exit jet power in ft lb/sec was found by integrating the products of jet velocity, jet area, and total pressure.

The final results of the machine integrations were in the following form:

$$C_{M_{total}} = \text{Base Moment} + \text{Jet Moment}/(\text{total lift}) (\text{Model length})$$

$$C_{M_{Base}} = \text{Base Moment}/(\text{total lift}) (\text{Model length})$$

11

$C_{M_{Jet}}$ = Jet Moment/(total lift) (Model length)

Also the three roll coefficients non-dimensionalized with model width.

Also

Total lift in pounds.
Total volume flow in ft^3/sec.
Total jet power in HP.

Figure 1
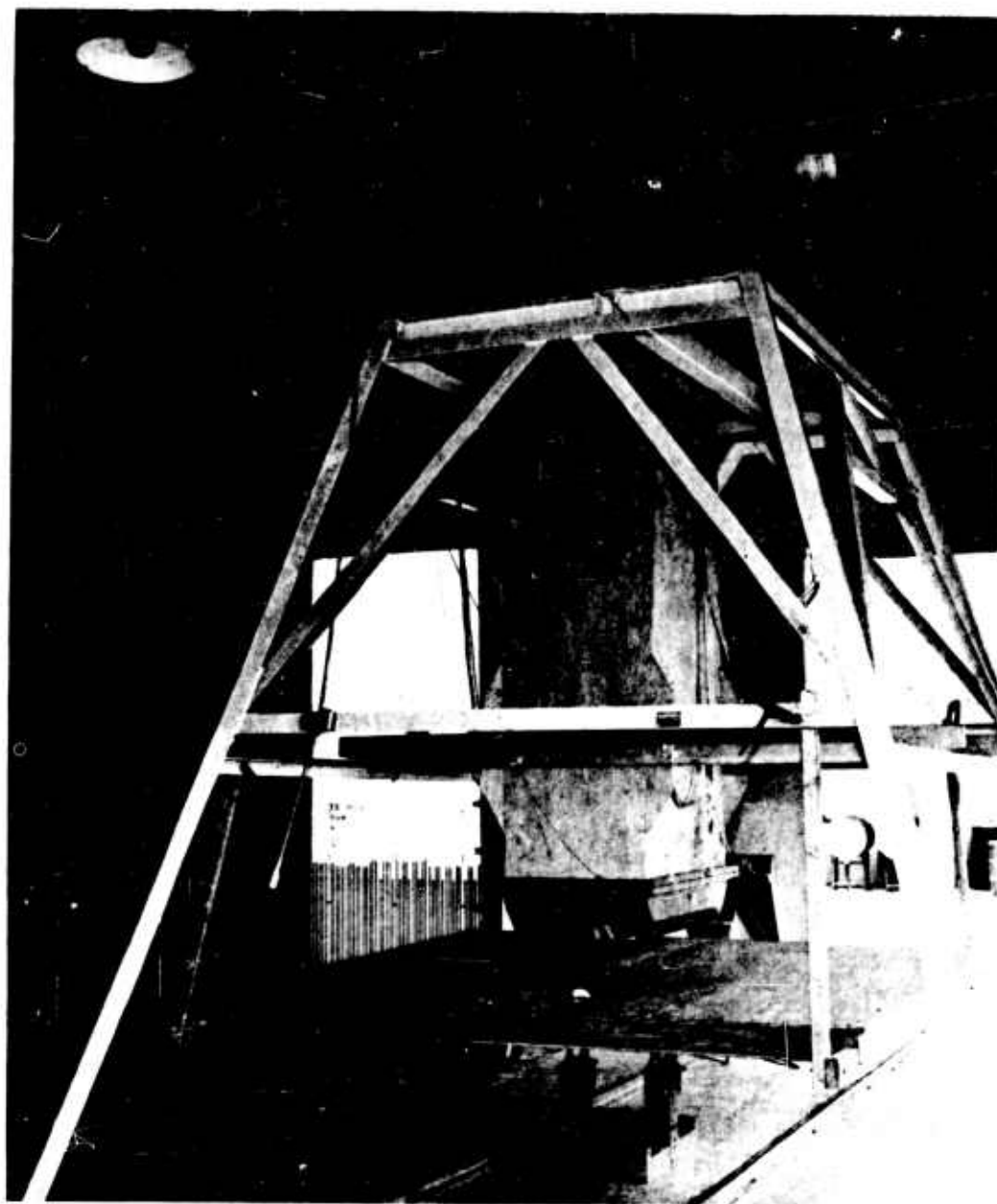
Hovering Test Facility (Photograph 10520)

Figure 2

AVAILABLE AND REQUIRED
PRESSURE AND FLOW
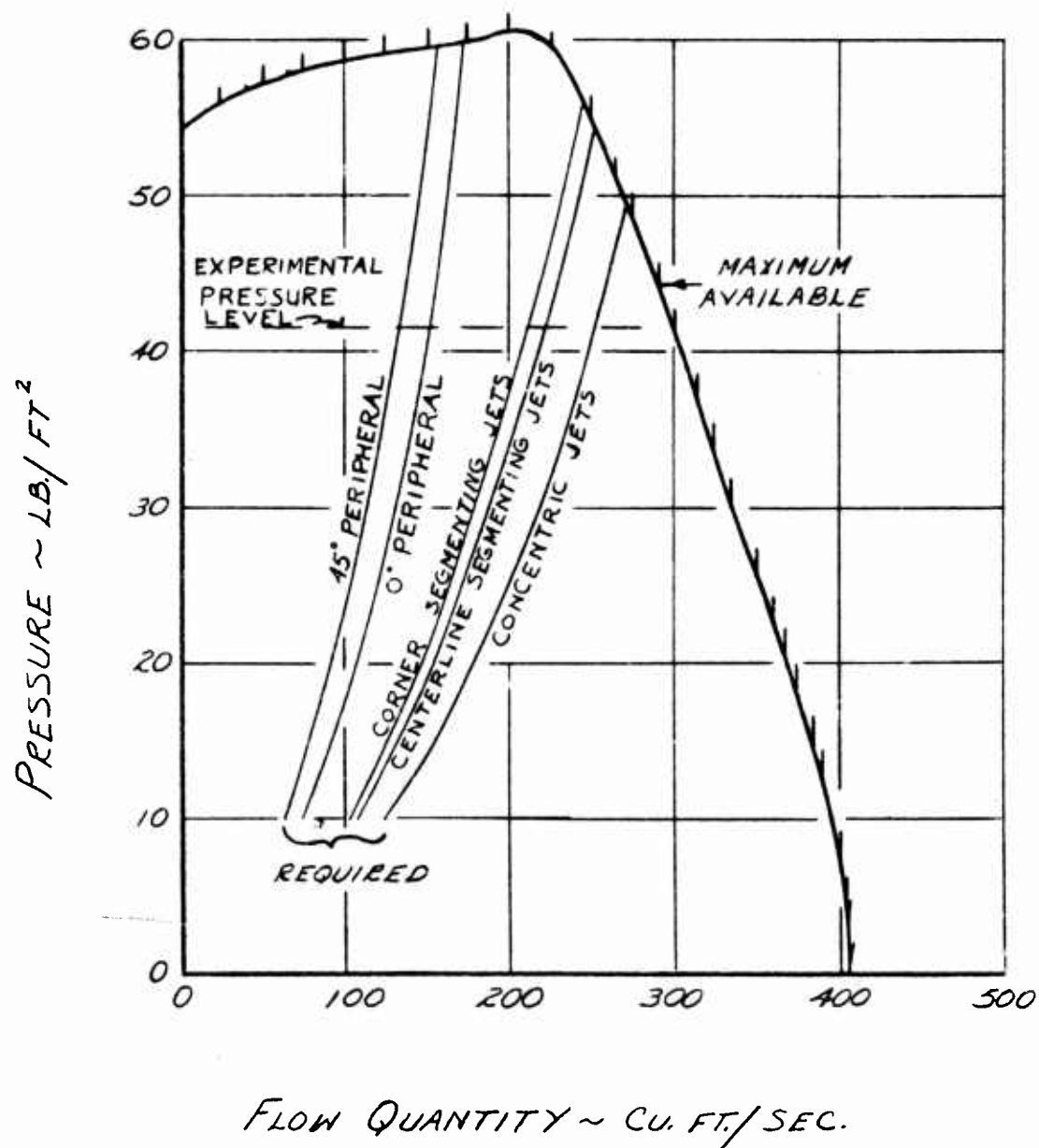
Figure 3
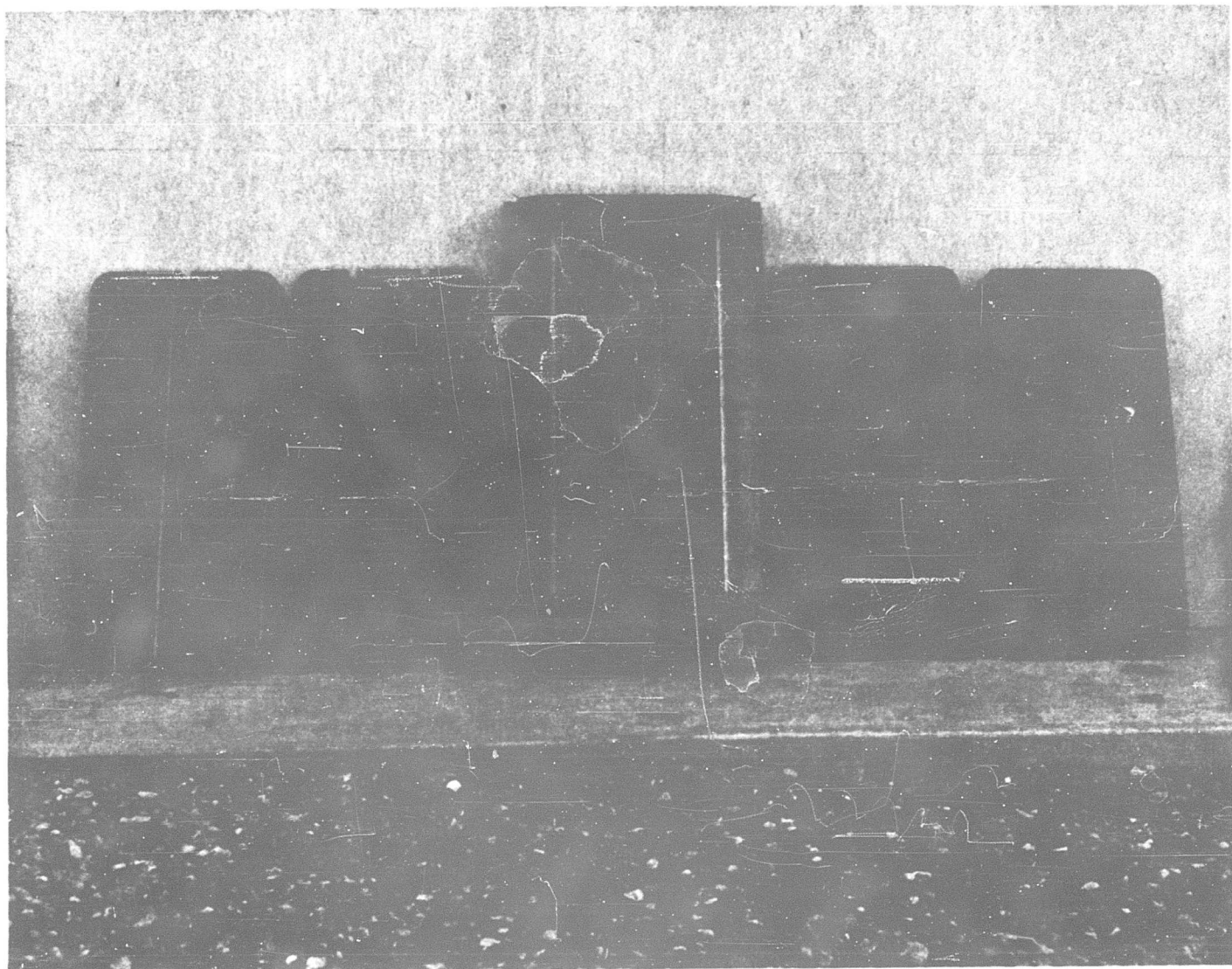
Three-Dimensional Model Bases (Photograph 10217)

VERTICAL PERIPHERAL JET MODEL
○ STATIC HEAD
× TOTAL HEAD

45° INCLINED PERIPHERAL JET MODEL

FIG 6
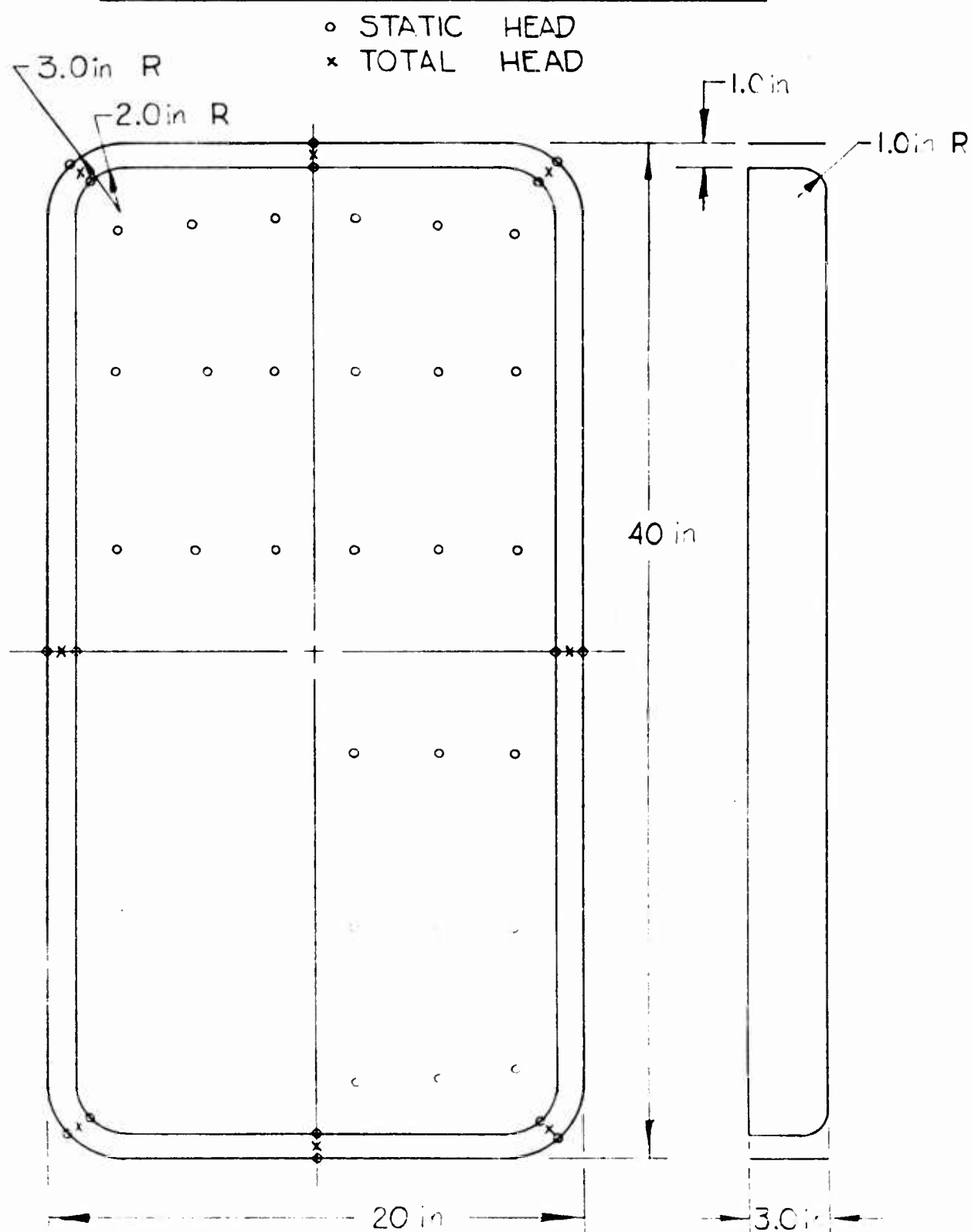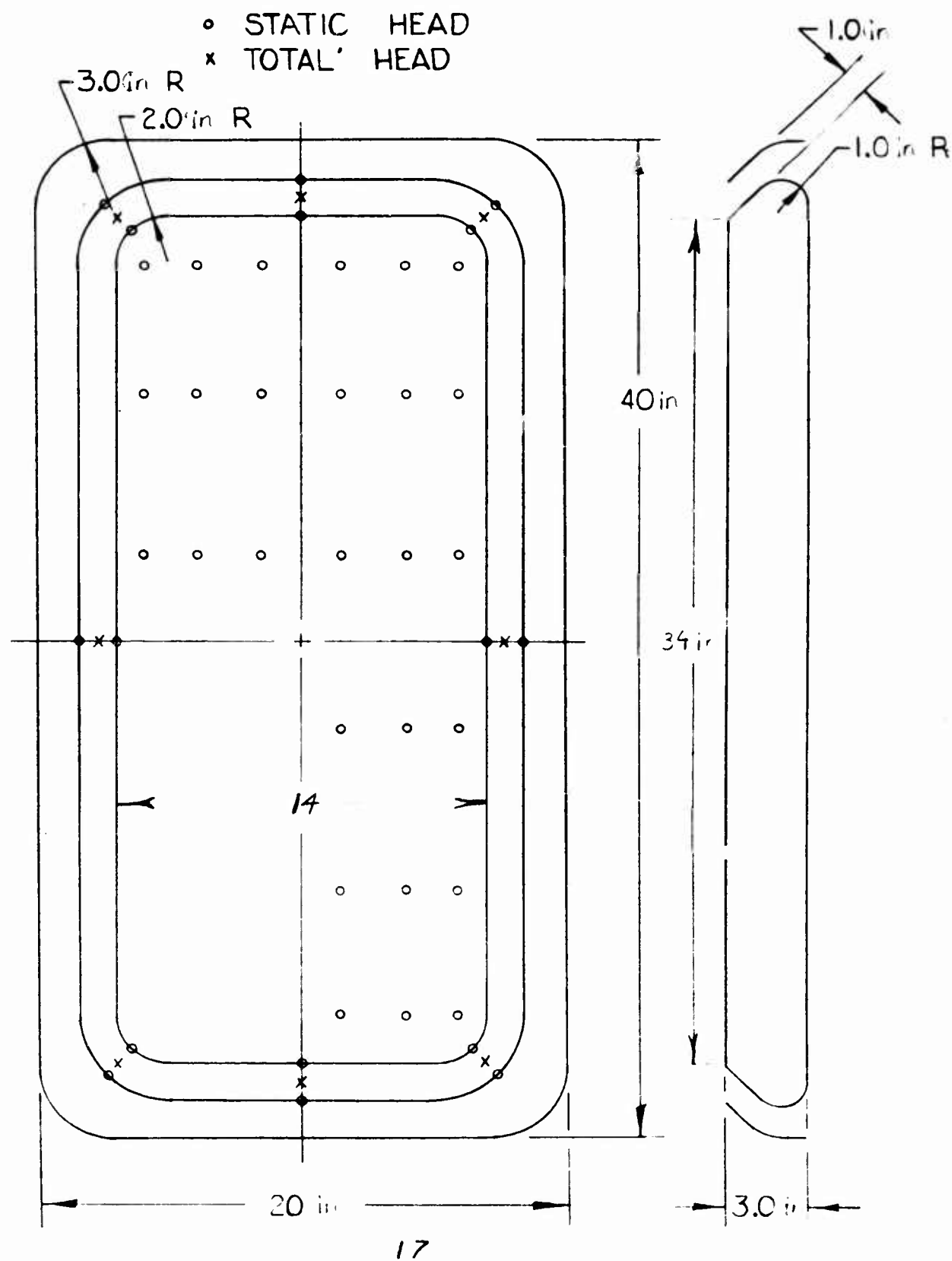
SHAPED BASE MODELS
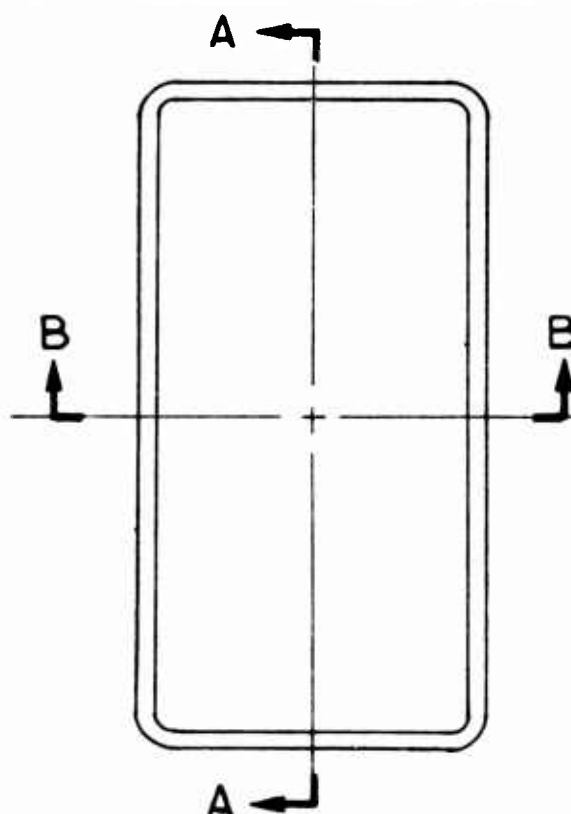
NOTE: INSTRUMENTATION AND JET CONFIGUR-
ATION IDENTICAL TO VERTICAL PERI-
PHERAL JET MODEL

	B-B	A-A
CONVEX	2.0 in 20 in	2.0 in 40 in
CONCAVE	2.0 in 20 in	2.0 in 4C in

18

FIG 7
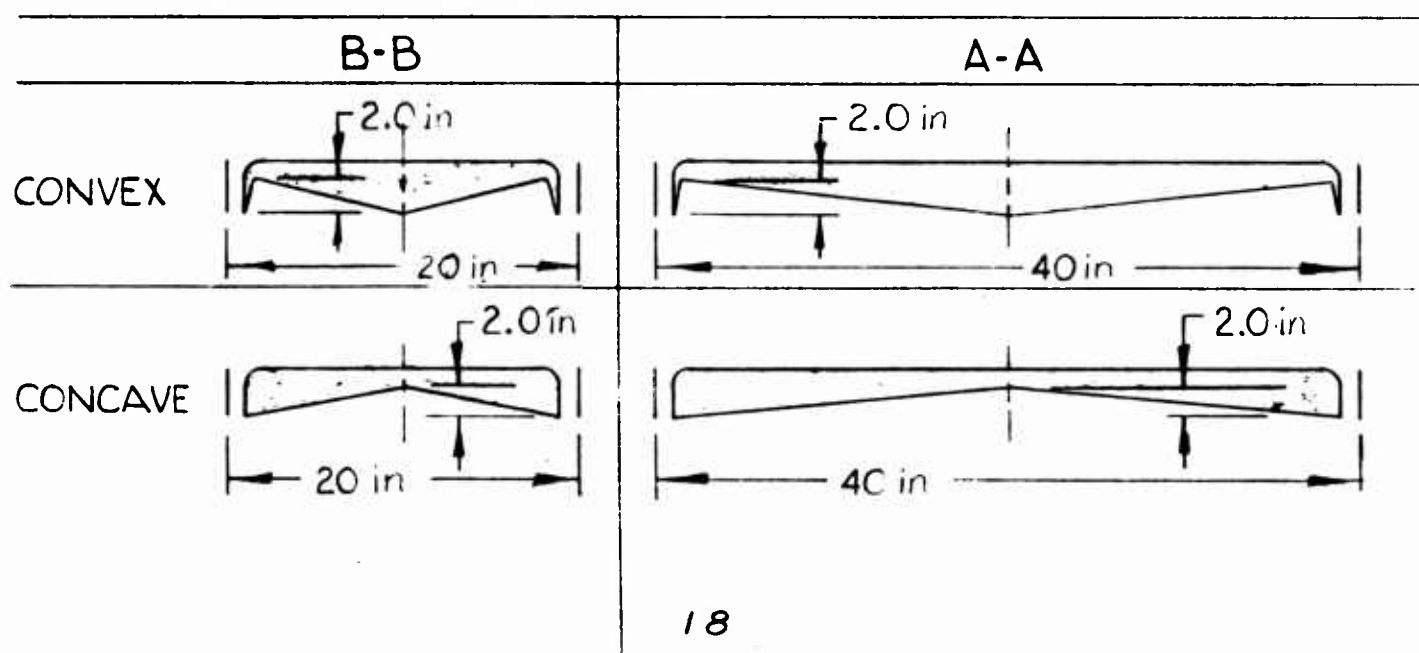
SKIRTED AND FLAP SEGMENTED MODELS

NOTE: INSTRUMENTATION & JET CONFIGURATION IDENTICAL TO VERTICAL PERIPHERAL JET MODEL

TYPICAL SECTION

6.0 in

6.0 in

6.0 in

11.0 in

6.0

22.0 in

FIG 8

CENTERLINE JET SEGMENTED MODEL
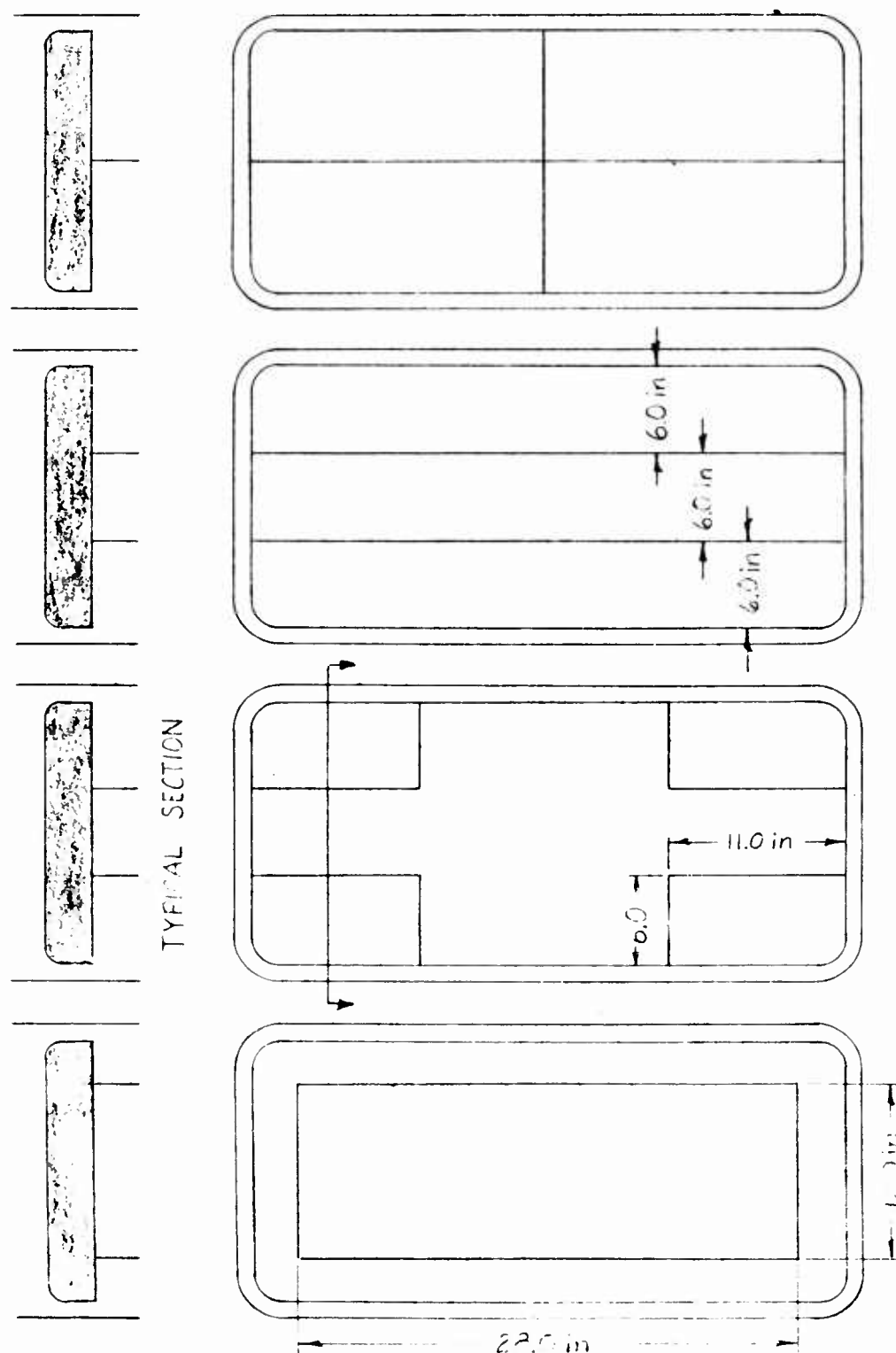
CENTERLINE JET SEGMENTED MODEL

○ STATIC HEAD
× TOTAL HEAD

CORNER LOBE JET SEGMENTED MODEL.

FIG 9

o STATIC HEAD
× TOTAL HEAD

CONCENTRIC JET SEGMENTED MODEL

FIG 10
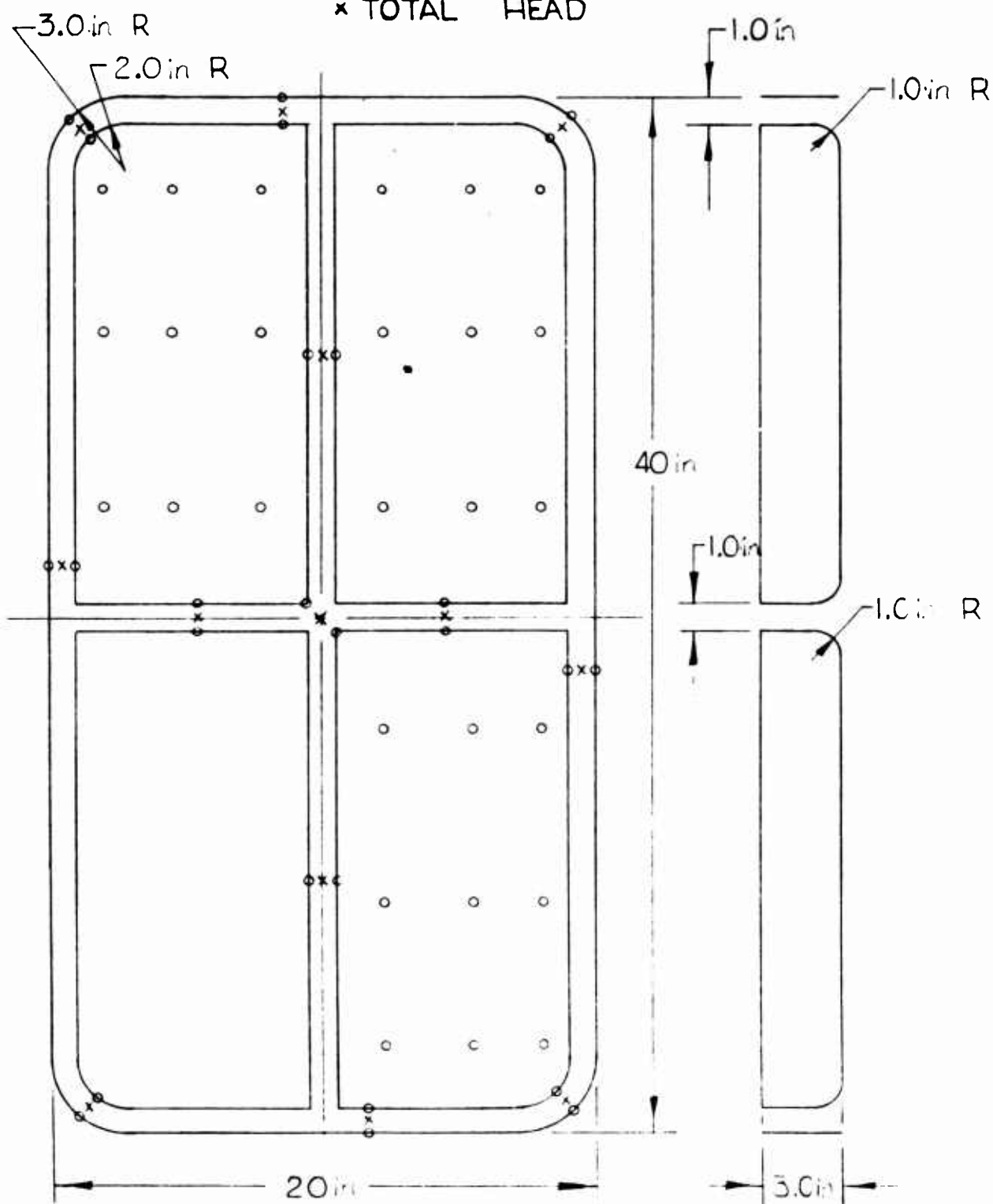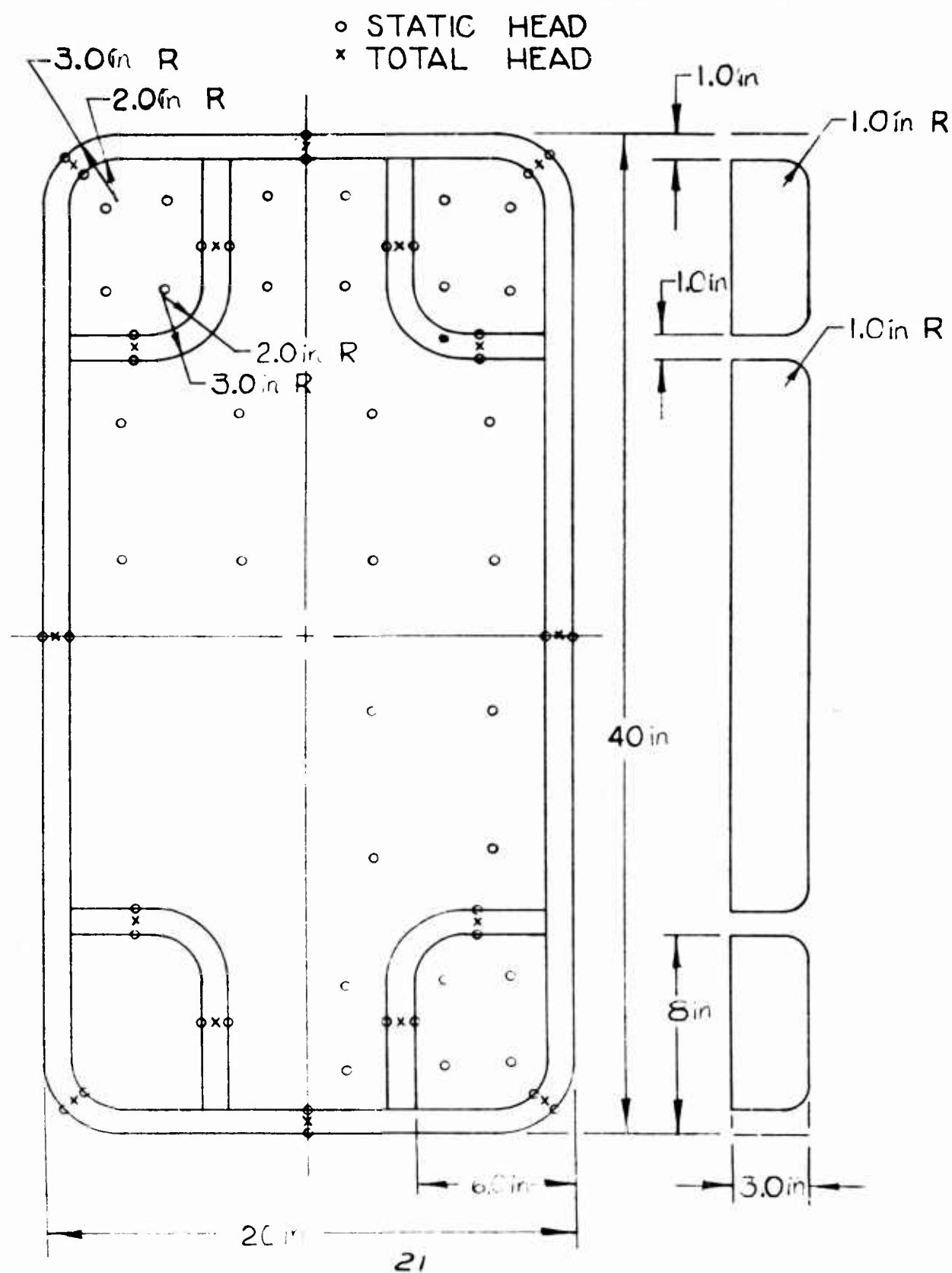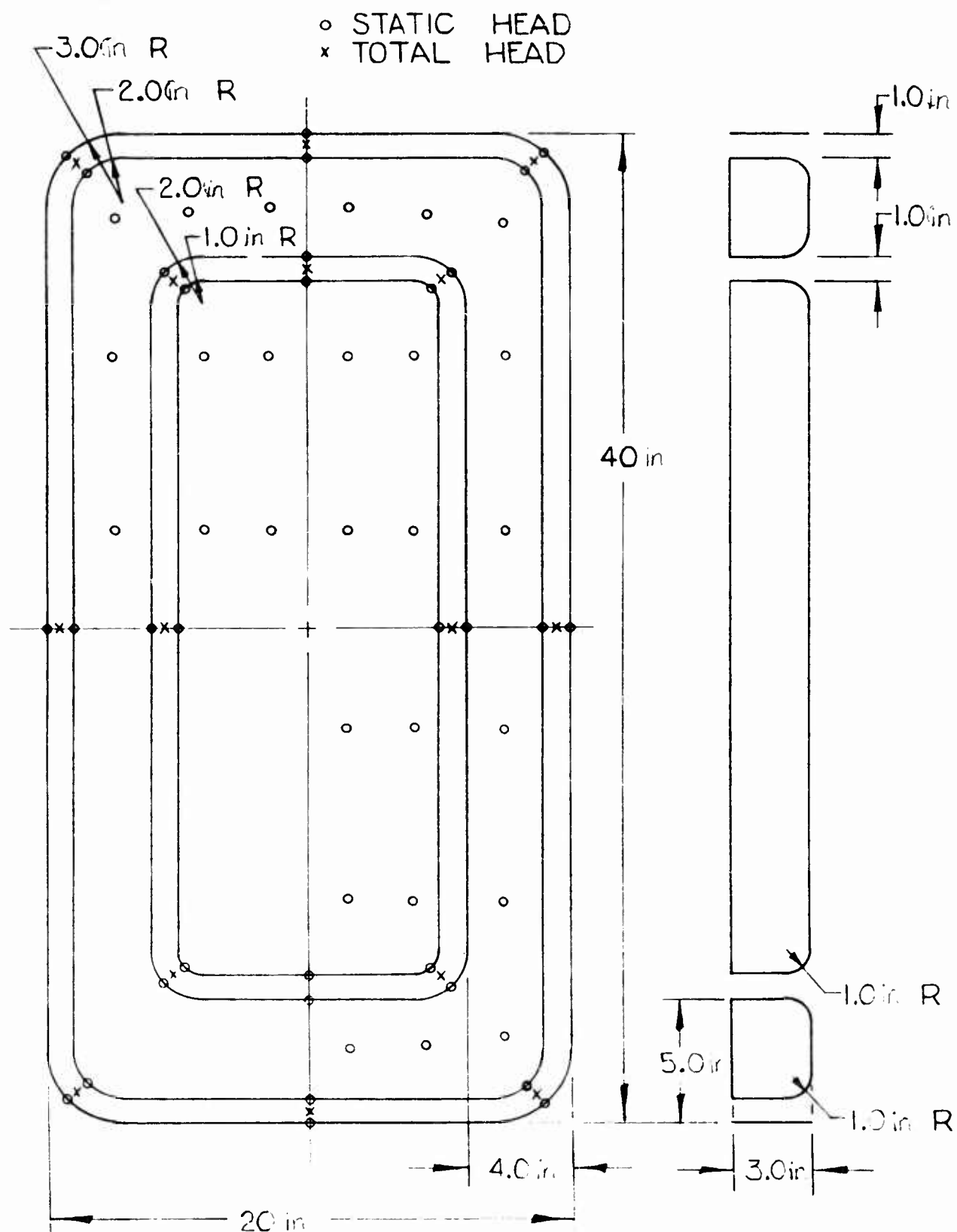
EXPERIMENTAL RESULTS

1. ## Longitudinal Stability

   a. ### Simple Peripheral Jet Models

   The base plus jet center of pressure shift of the vertical
   peripheral jet model is presented in Figure 11. The
   small angle slopes indicate static stability at $h/b = .05$,
   neutral stability at $h/b = .075$ and instability at larger
   values of h/b. At $h/b = .05$, the stability appears to
   decrease slightly at large pitch angles. At intermediate
   heights, the initial unstable slopes actually change to
   stable slopes at high pitch angles. At $h/b = .20$, this
   effect had not yet occurred at the highest angle tested.

   Figure 12 reveals that the base contribution to static
   stability becomes increasingly stable at high angles of
   pitch at all heights except $h/b = .20$. Examination of
   base pressure distribution indicates a softening of the
   unstable pressure gradients at high angle compared to
   moderate angles and a large local pressure increase near
   the low end. The base contribution is seen to be a large
   portion of the total and to a first approximation describe
   the complete model stability.

   The minor contribution of the jet is confirmed in Figure 13
   at all heights except $h/b = .05$. Here the jet contribution
   becomes large at the touchdown angle. When added to
   the base alone C. P. shift curve, the favorable trend in
   slope at high angles is reversed. At moderate and high
   heights, the jet contribution curves are systematic indi-
   cating a slightly stable influence up to moderate pitch
   angles followed by a slightly unstable influence at larger
   pitch angles. At angles very near touchdown (not covered
   at the higher heights in these experiments) an appreciable
   unstable jet contribution similar to that observed at

23

h/b = .05 would probably occur. The reason for this is
that the jet flow on the low end (and hence momentum
contribution to the reaction force) is severely reduced on
contact with the ground, whereas the jet on the high end
faces a minimum of back pressure, has a relatively
large momentum, and hence a relatively high reaction
force.

The base plus jet center of pressure shift of the 45°
inclined jet model is shown in Figure 14. Stable slopes
exist to higher values of h/b than for the vertical jet
model. Again, the base contribution to the stability is the
large one and the stability of the model is represented to
a first approximation by the base contribution. The
tendency for the base to become increasingly stable at
the higher pitch angles may be observed in Figure 15.
The jet contribution (Figure 16) is larger than it was
for the vertical jet model and varies from neutral at small
angles to unstable at larger pitch angles.

The static longitudinal stability derivative (for small
angles) $\partial C_M / \partial \alpha$ is shown in Figure 17 for the vertical
jet and for the 45° inclined jet models as a function of
the height in percent of length. The derivative is expressed
in percent center of pressure shift per degree of tilt to
obtain larger numbers than would occur if a pure decimal
system were used. A value of -.2 means that 5° of tilt
would result in a shift of the center of pressure 1% of
the length off the centerline toward the low side. The two
models have identical values at h/b = .05 and .20. The
45° jet model is clearly superior at all intermediate
height values. In particular, the 45° jet does not go
unstable until h/b exceeds .107, whereas the vertical jet
becomes unstable at h/b = .075.

The boundaries of pitch angle and height for stability are
compared for the two models by Figure 18. These simple
peripheral jet models are stable at all angles at the lower
heights but have the peculiar characteristic of regaining
stable slopes at high angles of pitch at those higher heights

24

where they are unstable for small pitch angles. This
tendency has been previously reported by the NASA
tests of annular jet models with length-width ratios
greater than one (Reference 5). The superiority of the
45° jet model at h/b = .13 and $\alpha \stackrel{>}{=} 10^O$ is clearly
indicated.

b.   Shaped Bases

Two-dimensional stability investigations conducted
previously at Aeronutronic[‡] suggested that proper shaping
of the base profile might (in the presence of cross flow)
produce a more stable base pressure distribution. Two
variations were investigated utilizing the simple vertical
peripheral jet model. In the concave version the base
sloped to a central recessed point. In the Convex version
the base was recessed just inboard of the inner jet wall
and sloped back to a central point which lay in the plane
of the jet exit.
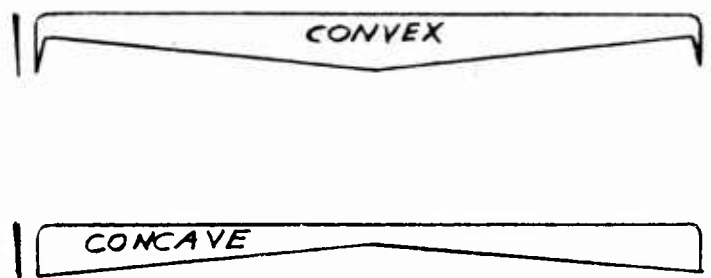
The magnitude of the recess was in each case 5% of the
model length or 10% of the width.

‡ Reference 1

25

The comparison of these configuration, base plus jet center of pressure shifts with that of the flat base is given in Figures 19 and 20. The convex base was stable at h/b = .05 and neutral at h/b = .075 similar to the flat base. At h/b = .10 all three configurations were very nearly alike. At h/b = .15 and .20 the convex was least unstable, and the concave base was intermediate between the convex base and the flat base. At these heights all three configurations were unstable.

Both the concave and the convex base exhibited increasing instability at the larger pitch angles in contrast to the flat base which exhibited improved stability at the larger pitch angles. These experiments,although very brief, do not hold out much hope for base shaping as a method of obtaining hovering static stability.

c.   Skirted and Flap Segmented Models

Aeronutronic is actively studying the flexible skirt concept as a means of reducing required flow quantities and power requirements. If this should prove practical, it will be of interest to know what influence the skirt will have on the stability problem. If a long flexible peripheral flap is practical, it should also be possible to segment the base with long flexible flaps. These could perhaps replace base segmenting jets as a means of improving hovering stability.

A rigid skirt of length = 5% of the model length was added to the model as an extension of the outer nozzle wall. In addition, the base was segmented by various rigid flaps. All stability runs were conducted at height (measured to the model base) of either 7.5% or 10% of the model length. The clearance beneath the skirt is therefore either 2.5% or 5%.. The skirt reaches either two-thirds or one half the way to the ground.

The base plus jet center of pressure shift is compared for several configurations in Figure 21. The addition of the skirt alone did not markedly improve the static stability.

26

The concentric flap changed the neutral stability at
$h/b = .075$ to slightly stable, but was not adequate to
provide stability at $h/b = .10$. The corner lobe and
centerline base segmenting flaps provided static sta-
bility at $h/b = .075$ and $.10$. The centerline flaps were
superior to the other types. The magnitude of the C. P.
shift was small because the long skirt limited the pitch
angles to modest values. The jet contribution is small
and the base contribution describes to a first approxi-
mation the stability behavior of the model. In general
the stability improves at the higher pitch angles.

The stability derivative $\partial C_M / \partial \alpha$ for small angles is
shown in Figure 22. The degree of static stability for
the skirted and flapped models is seen to decrease rapidly
with increasing height similar to the basic model. The
order of improvement in stability from the basic to the
concentric to the corner lobe to the centerline configu-
ration is clearly indicated. In general, the flap is very
effective when it extends two-thirds of the way to the
ground, and is losing effectiveness rapidly when it
extends only half way to the ground.

d.   Jet Segmented Models

Jet segmentation of the base is the accepted method of
augmenting the static hovering stability of annular jet
air-cushion vehicles (Reference 6). The most general
formulation of the problem would be, "What is the geometry
of jet segmentation which will provide a given level of
static stability at high values of h/b while retaining the
highest possible performance". Several problems are
immediately apparent. It is not clear what level of
stability is desirable. If a level is arbitrarily decided
upon, one must still define what is meant by performance.
Air-cushion vehicles (for a variety of reasons) do not

employ peripheral jets which are optimized for hovering performance. The percent change in performance due to segmenting jets will vary depending on how close or far one is from optimum hovering geometry. It is not possible at present to compute the amount of jet segmentation required to provide a given level of stability. The lift and power of a jet segmented configuration is likewise not accurately predictable.

In view of the above dilemma, a simple experimental program was employed to gain some working experience with the problem and to provide inputs for follow-on analytical work which might eventually provide a general solution.

The basic 40" by 20" rectangular vertical peripheral jet was used as the reference model. The base was replaced with centerline, corner lobe, and concentric, segmenting jet bases in succession. All models had one-inch wide peripheral and segmenting jets and the total pressure in the jet was set at 41.5 pounds per square foot.

The base plus jet center of pressure shift is given in Figure 23 for the centerline jet segmented model. The stability for small angles is high at low and moderate heights and becomes lower at the higher heights. Instability occurs at large angles. This change from stable for small angles to unstable at large angles is the reverse of the situation for the basic model at high heights where the model had an unstable slope at low angles and became stable at high angles. It should be noted that the centerline jet segmented model is stable in pitch (at small angles) at all heights tested including 20% of the model length. The base center of pressure shift curves given in Figure 24 are very similar to the total C.P. curves except that the decrease in stability at large angles is less pronounced. The jet contribution given in Figure 25 shows little effect up to moderate angles but a significant de-stabilizing tendency at high angles.

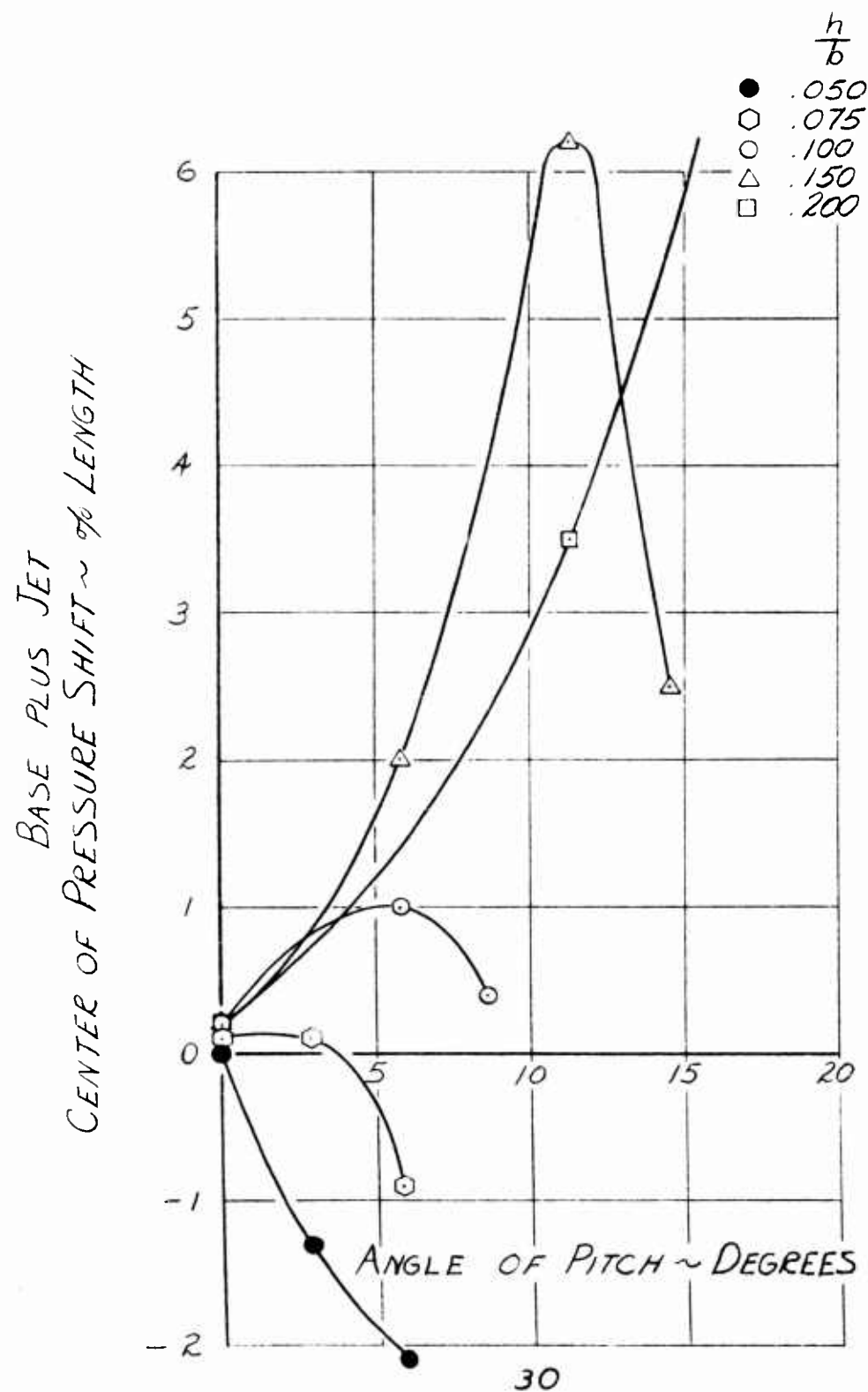The base plus jet center of pressure shift is given for the corner lobe jet segmented model in Figure 26. The nature of the curves are very similar to those of the centerline jet segmented model but the stability is not as high. Instability again appears at high tilt angles at high heights. The base contribution (Figure 27) and jet contribution (Figure 28) tell a very similar story to the centerline jet segmented model.

The base plus jet center of pressure shift is given for the concentric jet segmented model in Figure 29. The model is stable at all heights although the degree of stability is lower than demonstrated by the two previous jet segmented models. The concentric jet goes unstable at the highest height angle combination. The base contribution is shown by Figure 30 to be the stabilizing term and the jet contribution of Figure 31 exhibits a large unstable contribution at large h and α .
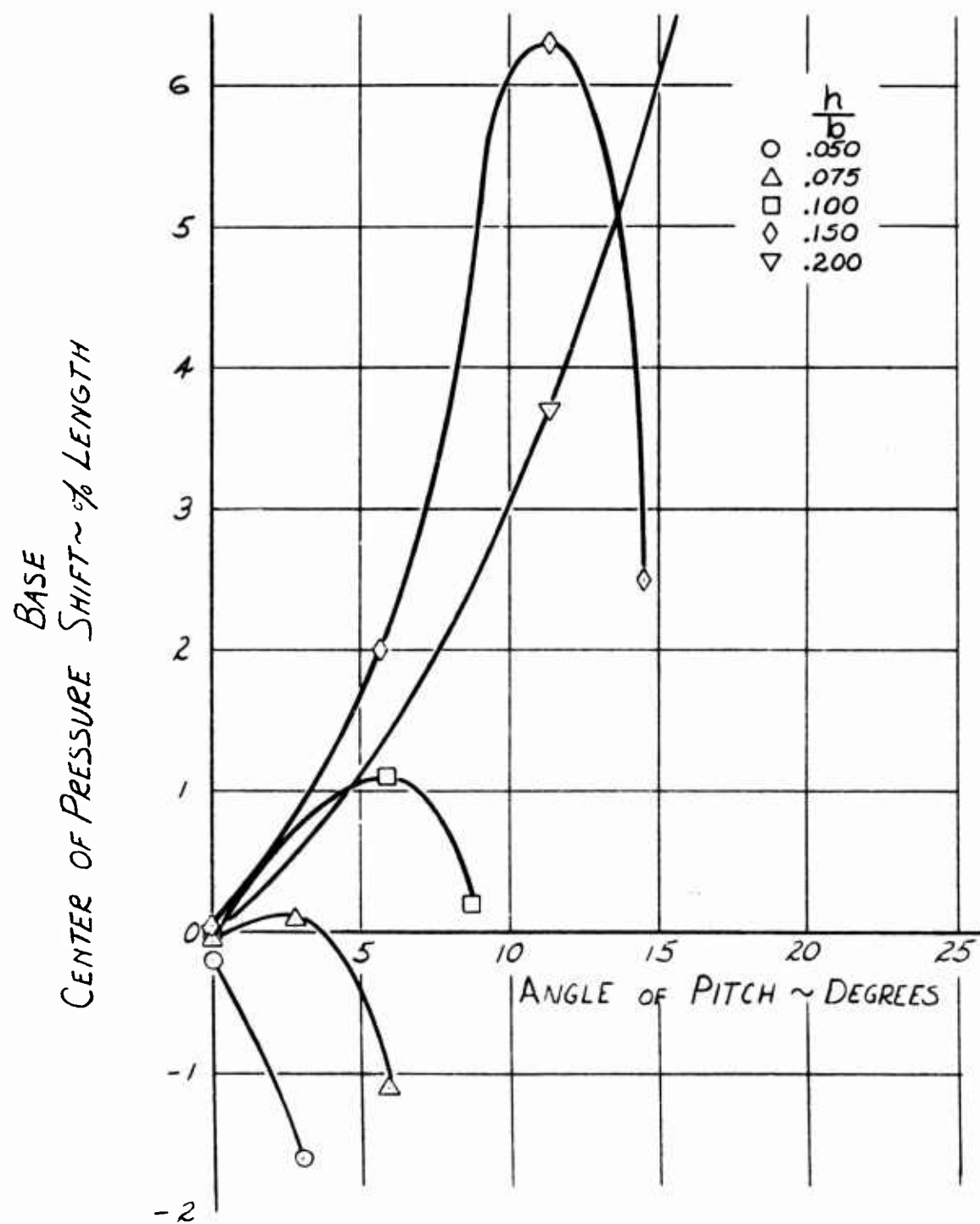
The small angle stability data for the jet segmented models is summarized in Figure 32. All three configurations are stable at all heights tested through 20% of the model length. The concentric jet had the lowest stability, the corner lobe configuration had somewhat higher stability, and the centerline jet configuration had the highest stability.

The effect of jet segmentation on height-pitch angle stability boundaries is illustrated by Figure 33. High tilt angle instability is encountered on the centerline jet model at $h/d >$ .08, on the corner lobe model at $h/d >$ .12, and on the concentric jet model at $h/d >$ .16. Thus, we see that order of preference on high tilt angle stability is just the reverse of the order of preference on the magnitude of the low tilt angle stability.
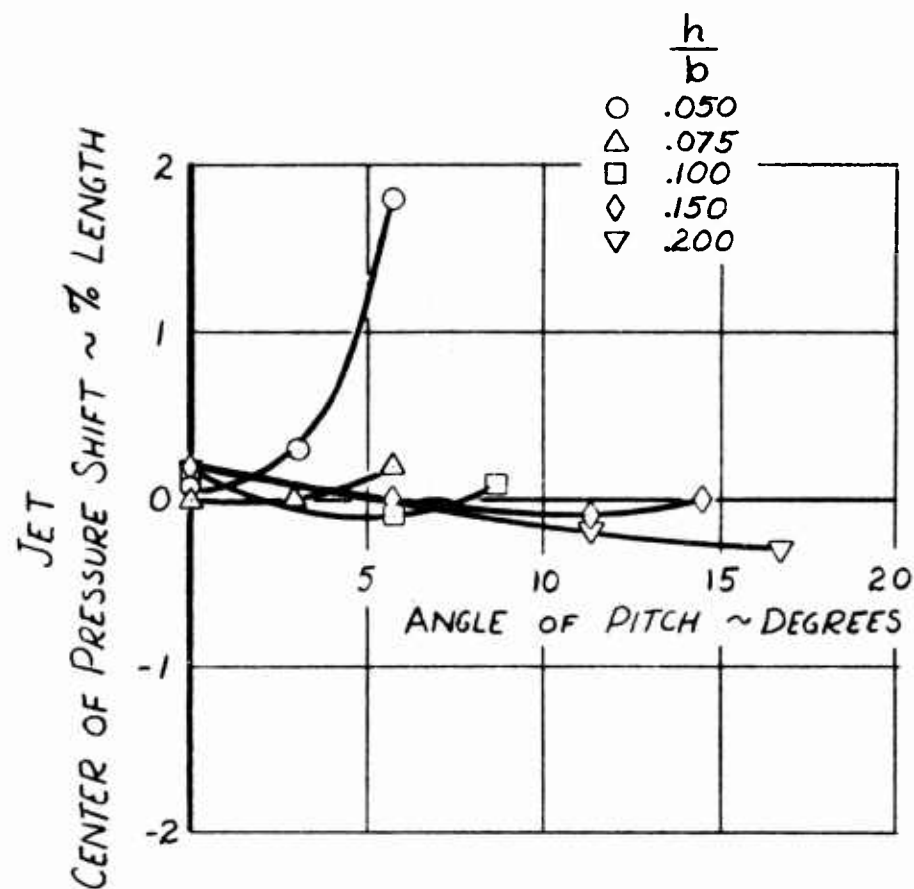
Figure 11

VERTICAL PERIPHERAL JET MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 12

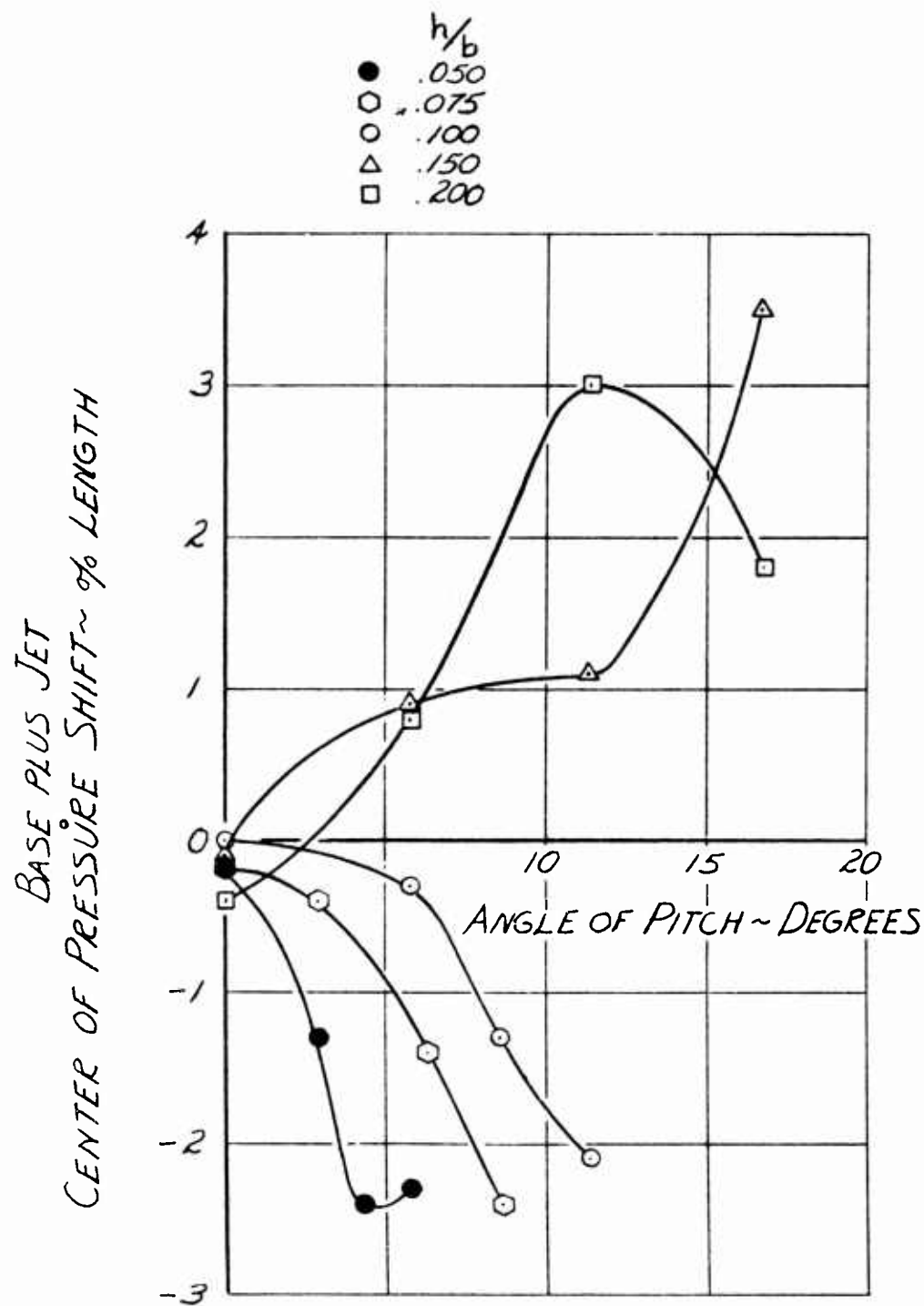VERTICAL PERIPHERAL JET MODEL
BASE CENTER OF PRESSURE SHIFT

$\frac{h}{b}$

O	.050
△	.075
□	.100
◇	.150
▽	.200

BASE
CENTER OF PRESSURE SHIFT ~ % LENGTH

ANGLE OF PITCH ~ DEGREES

Figure 13

VERTICAL PERIPHERAL JET MODEL
JET CENTER OF PRESSURE SHIFT

Figure 14

45° INCLINED PERIPHERAL JET MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

33

45° Inclined Peripheral Jet Model
Base
Center of Pressure Shift

Figure 15
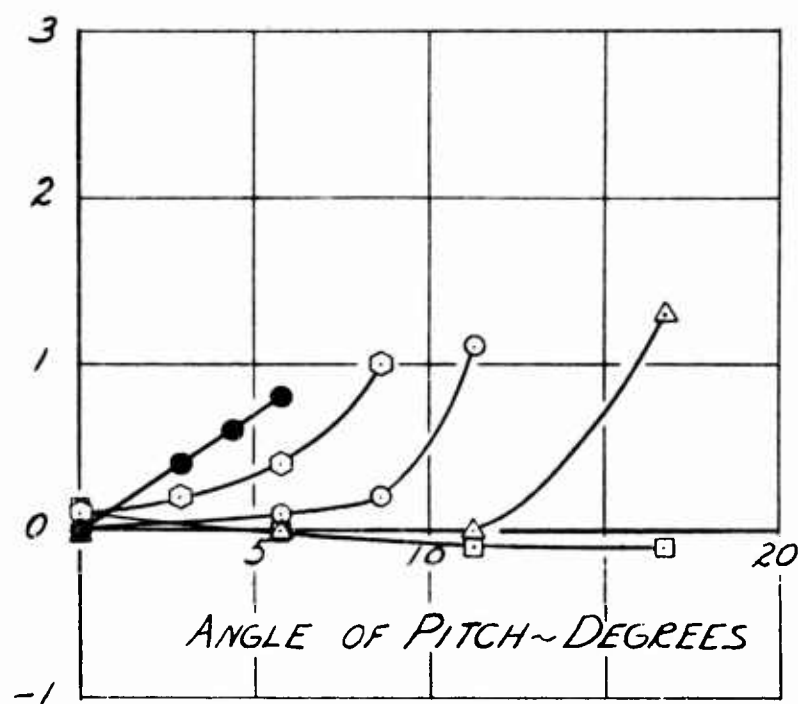
Figure 16

45° INCLINED PERIPHERAL JET MODEL
JET
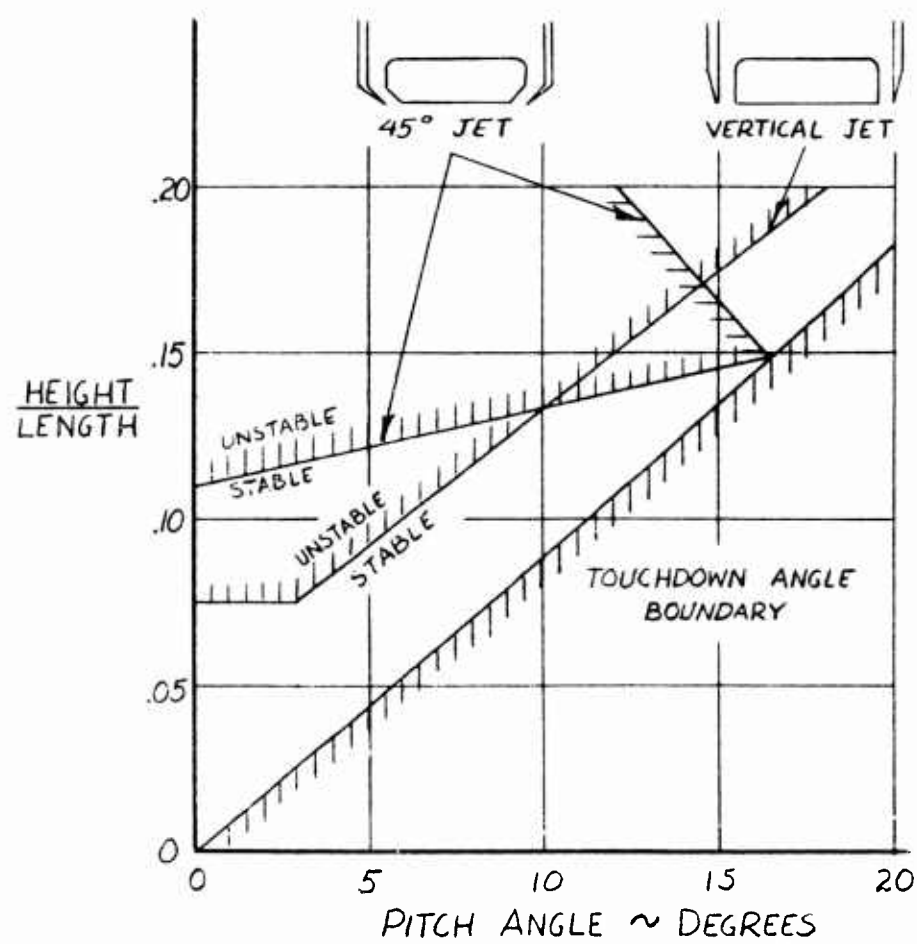### CENTER OF PRESSURE SHIFT

Figure 17

STATIC LONGITUDINAL HOVERING STABILITY
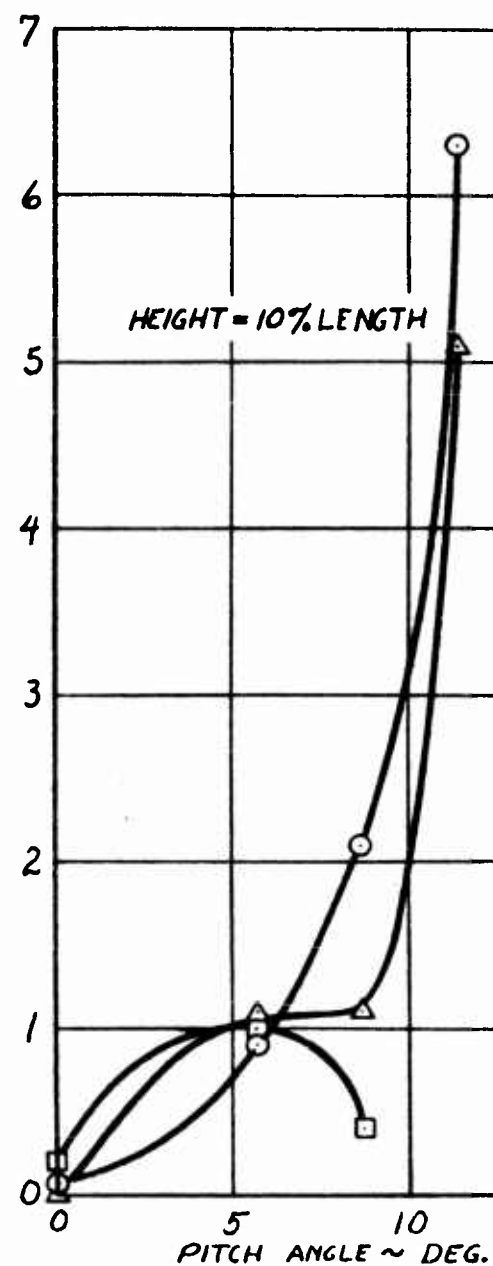
VERTICAL vs. 45° INCLINED JET

36
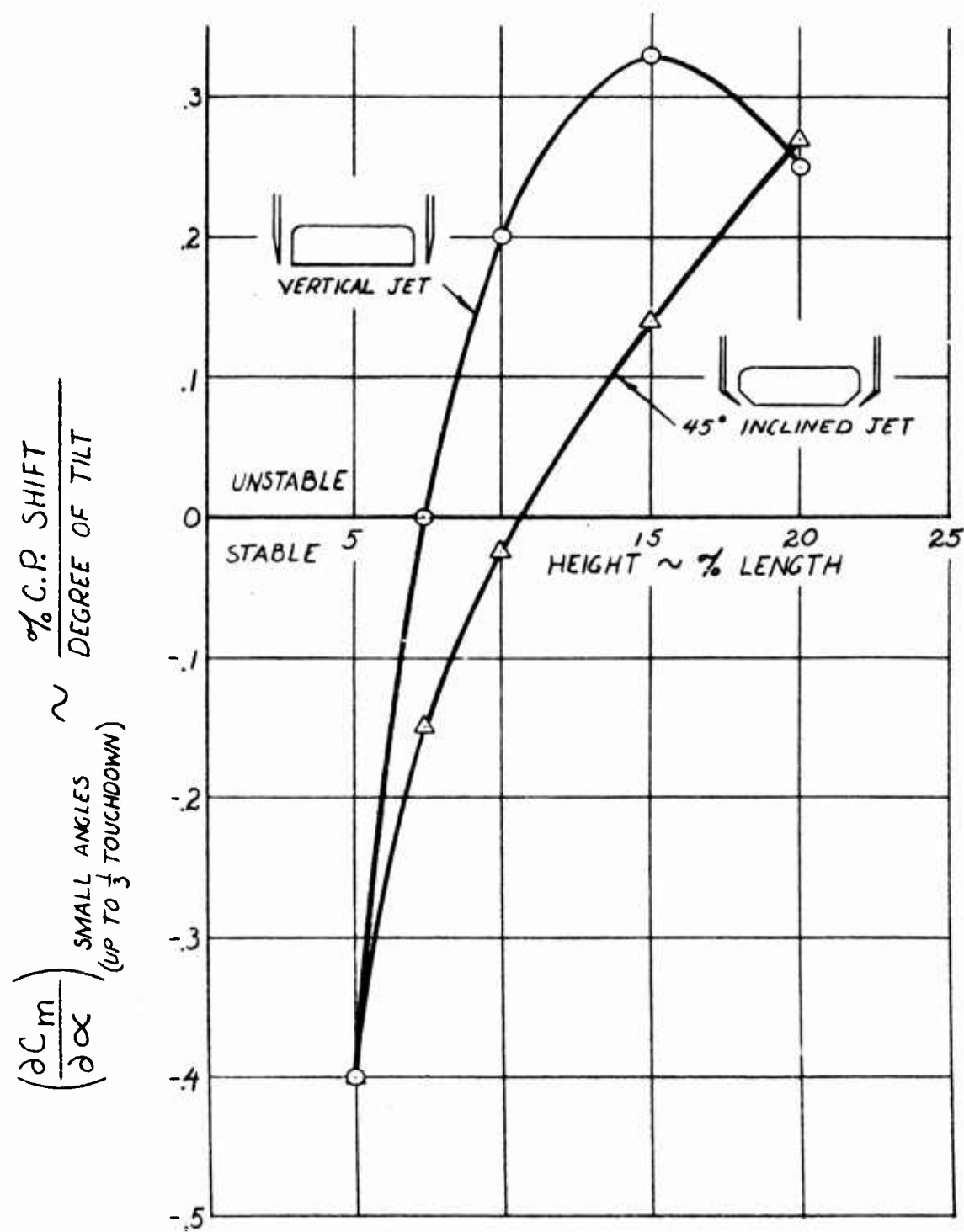
Figure 18

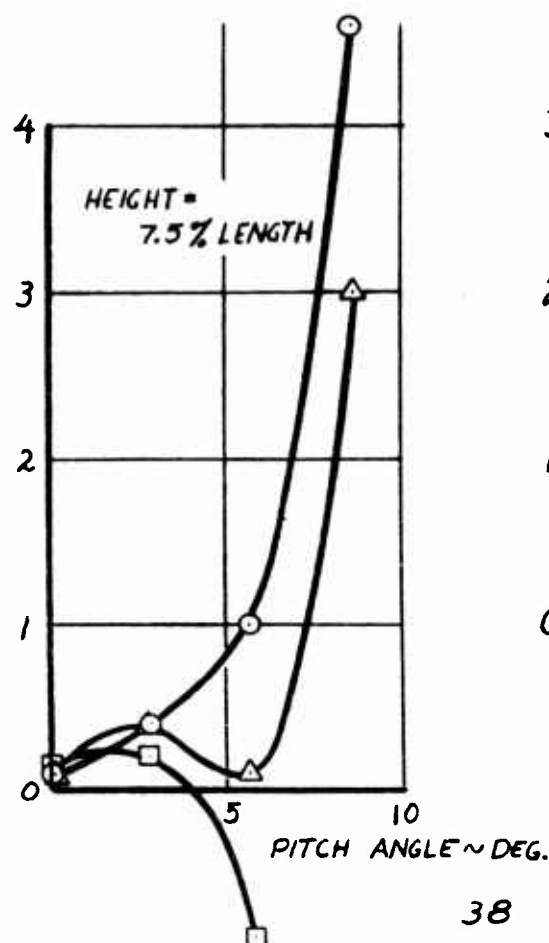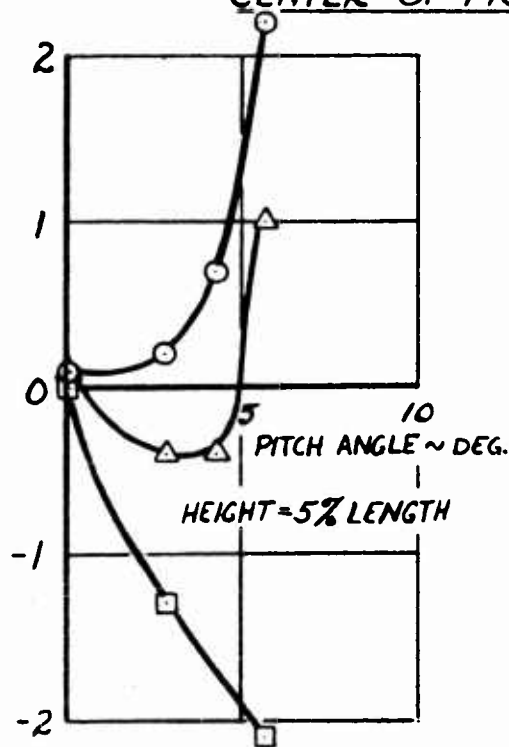HEIGHT-PITCH ANGLE STABILITY BOUNDARIES
VERTICAL vs 45° INCLINED JET

EFFECT OF BASE SHAPING ON BASE PLUS JET CENTER OF PRESSURE SHIFT

Figure 19

38

Figure 20

EFFECT OF BASE SHAPING ON BASE PLUS JET

CENTER OF PRESSURE SHIFT

39

Figure 21
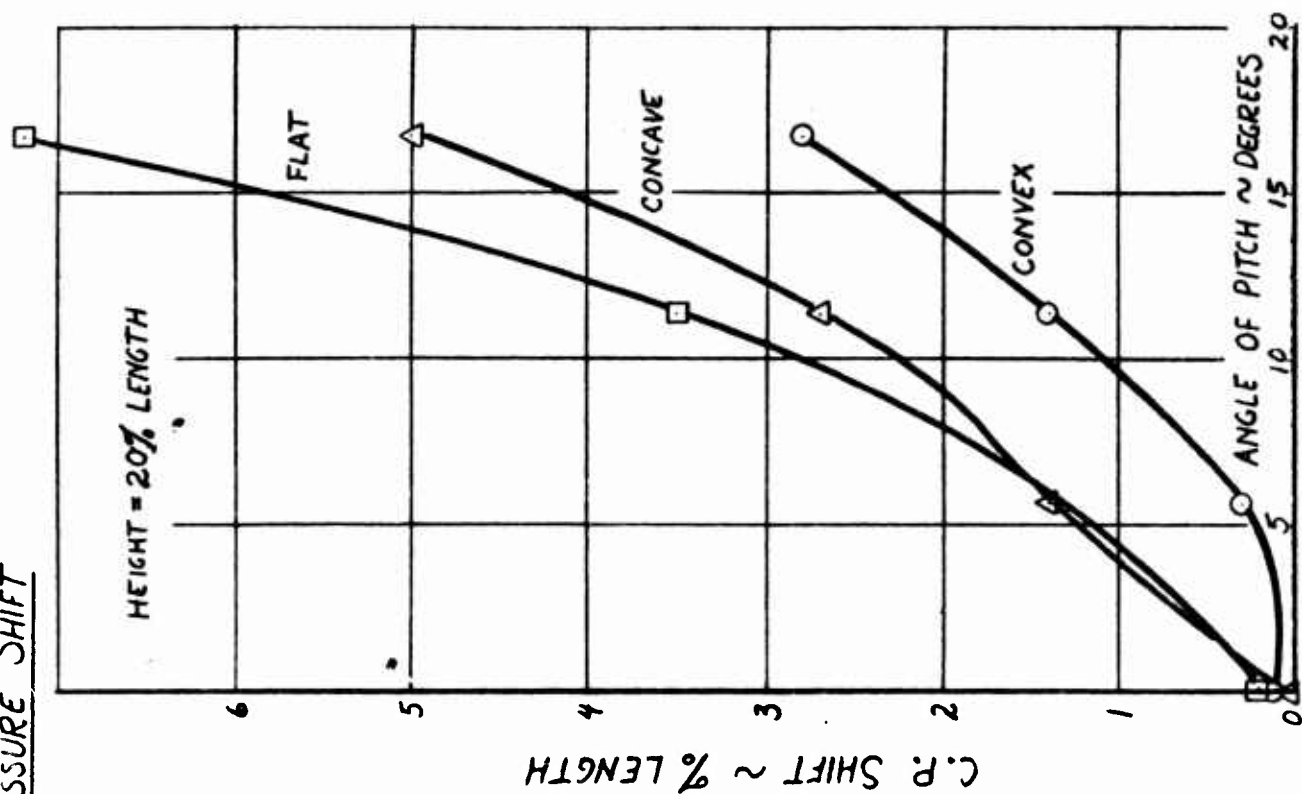
EFFECT OF SKIRT AND FLAPS
ON BASE PLUS JET
CENTER OF PRESSURE SHIFT

40
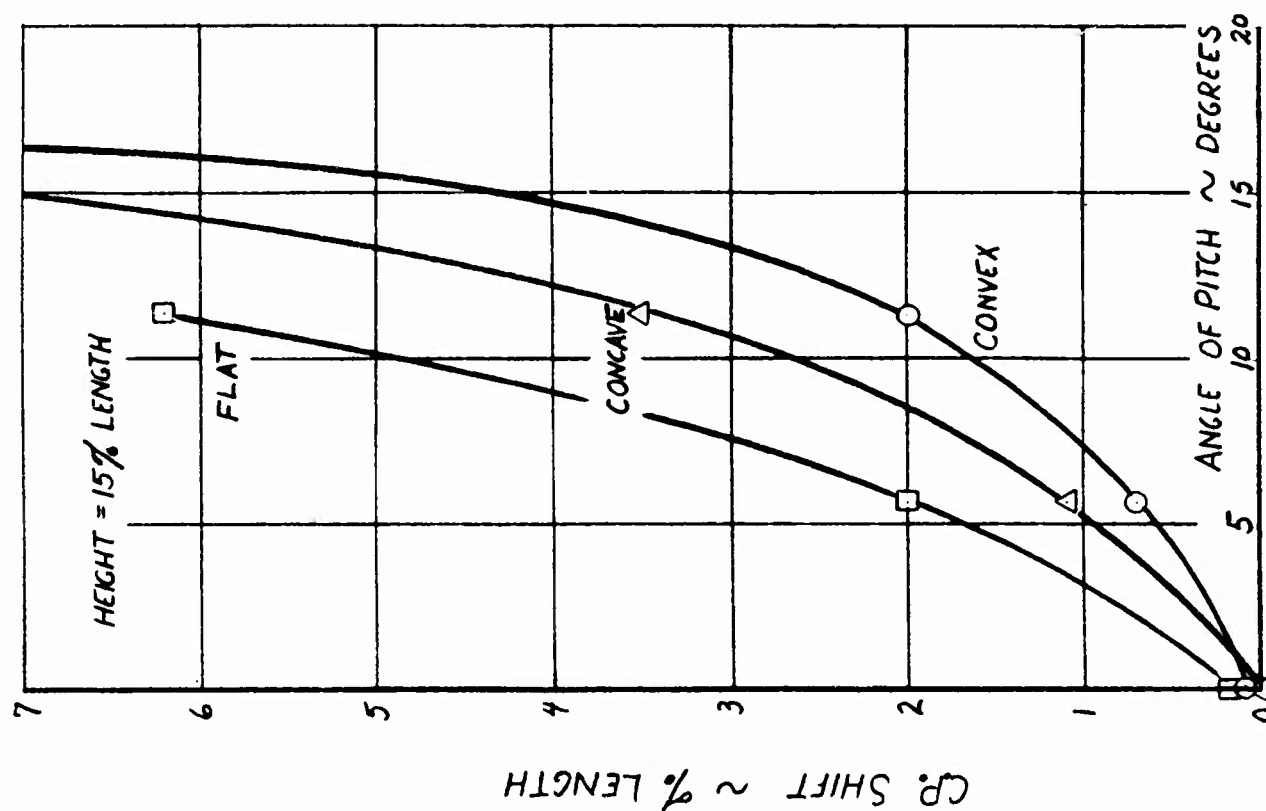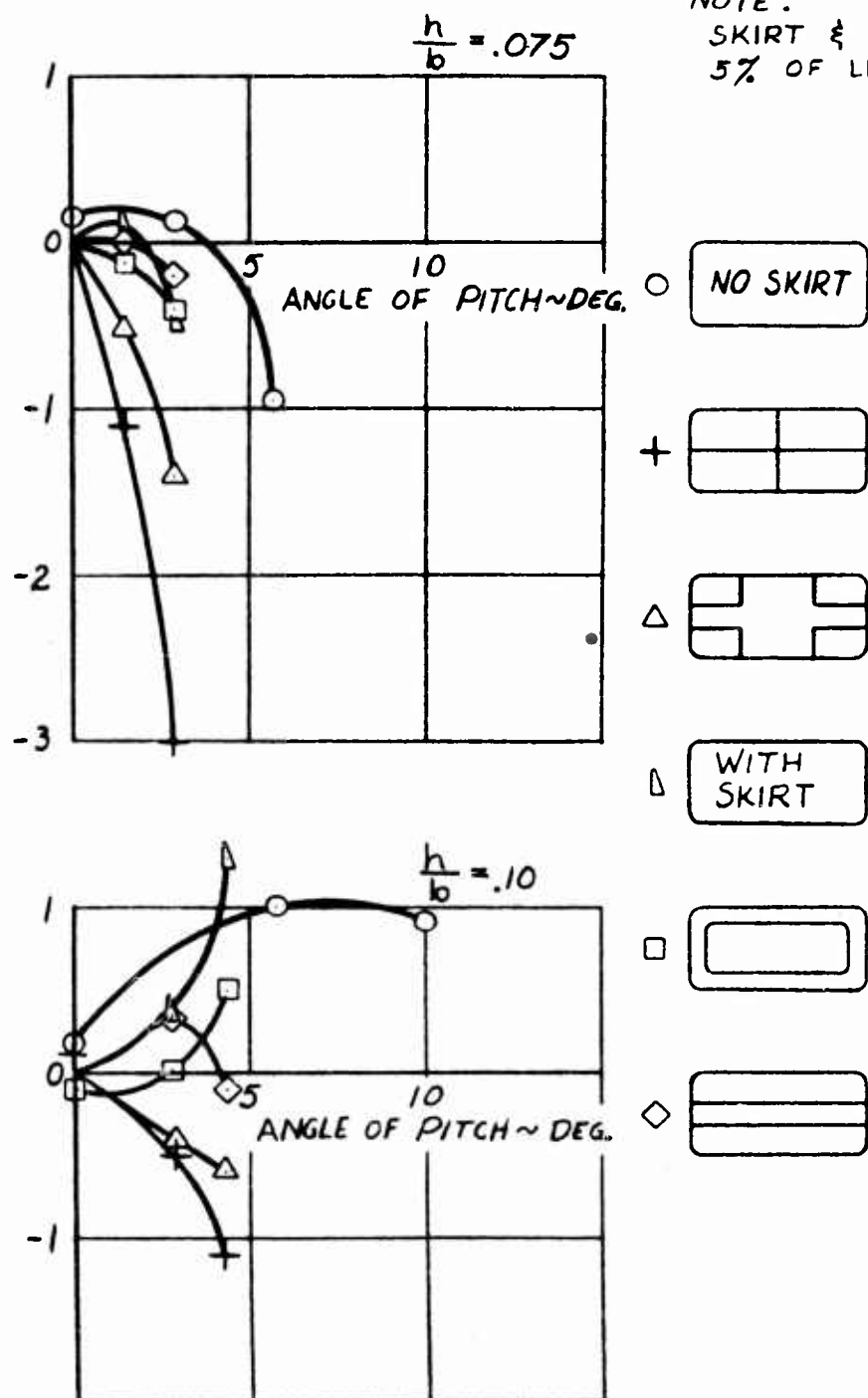
EFFECT OF 5% LENGTH SKIRT AND FLAPS ON STATIC LONGITUDINAL HOVERING STABILITY

Figure 22
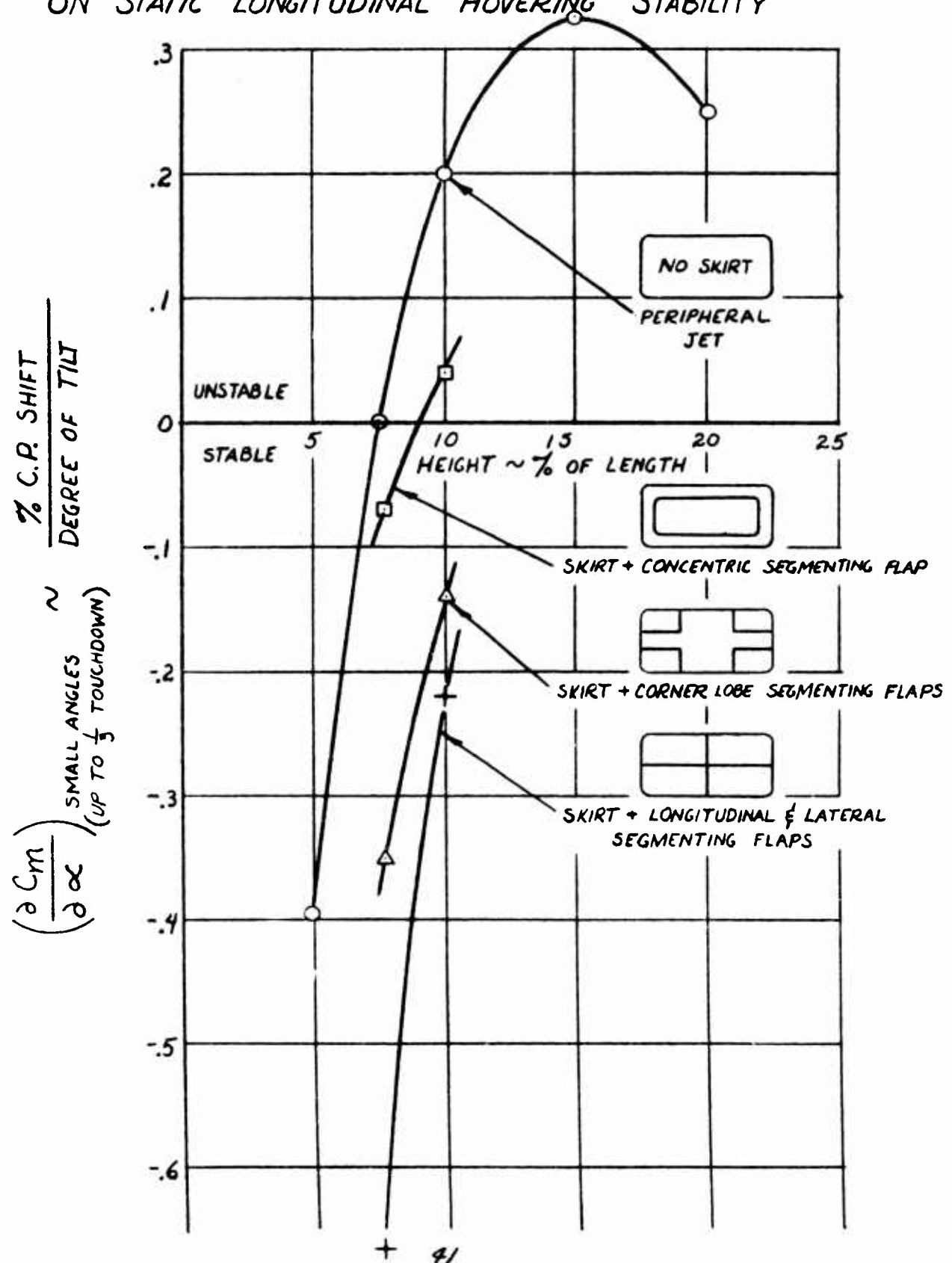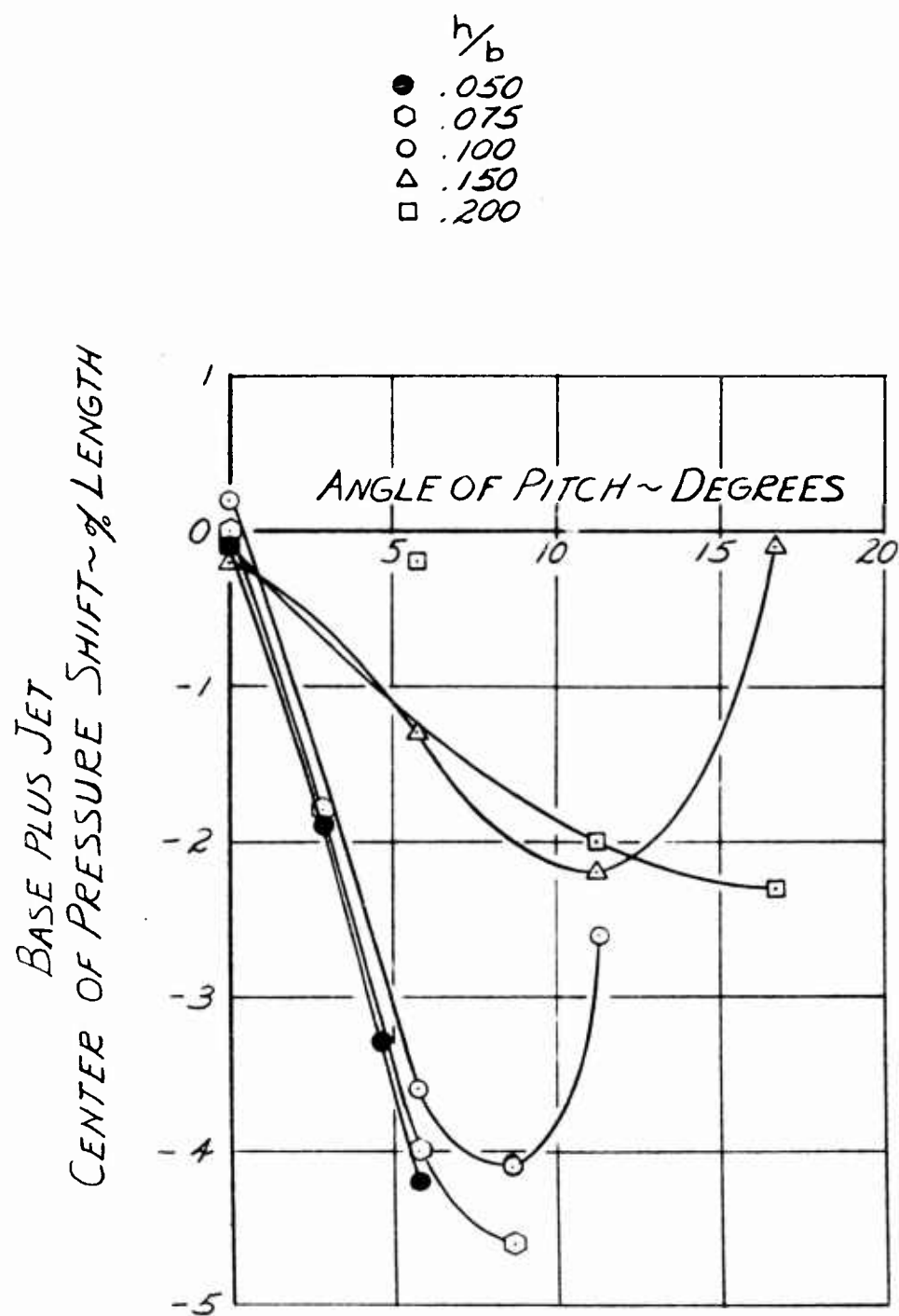
Figure 23

CENTERLINE JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 24

CENTERLINE JET SEGMENTED MODEL
BASE
CENTER OF PRESSURE SHIFT

43

Figure 25

CENTERLINE JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT

44

Figure 26

CORNER LOBE JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

45
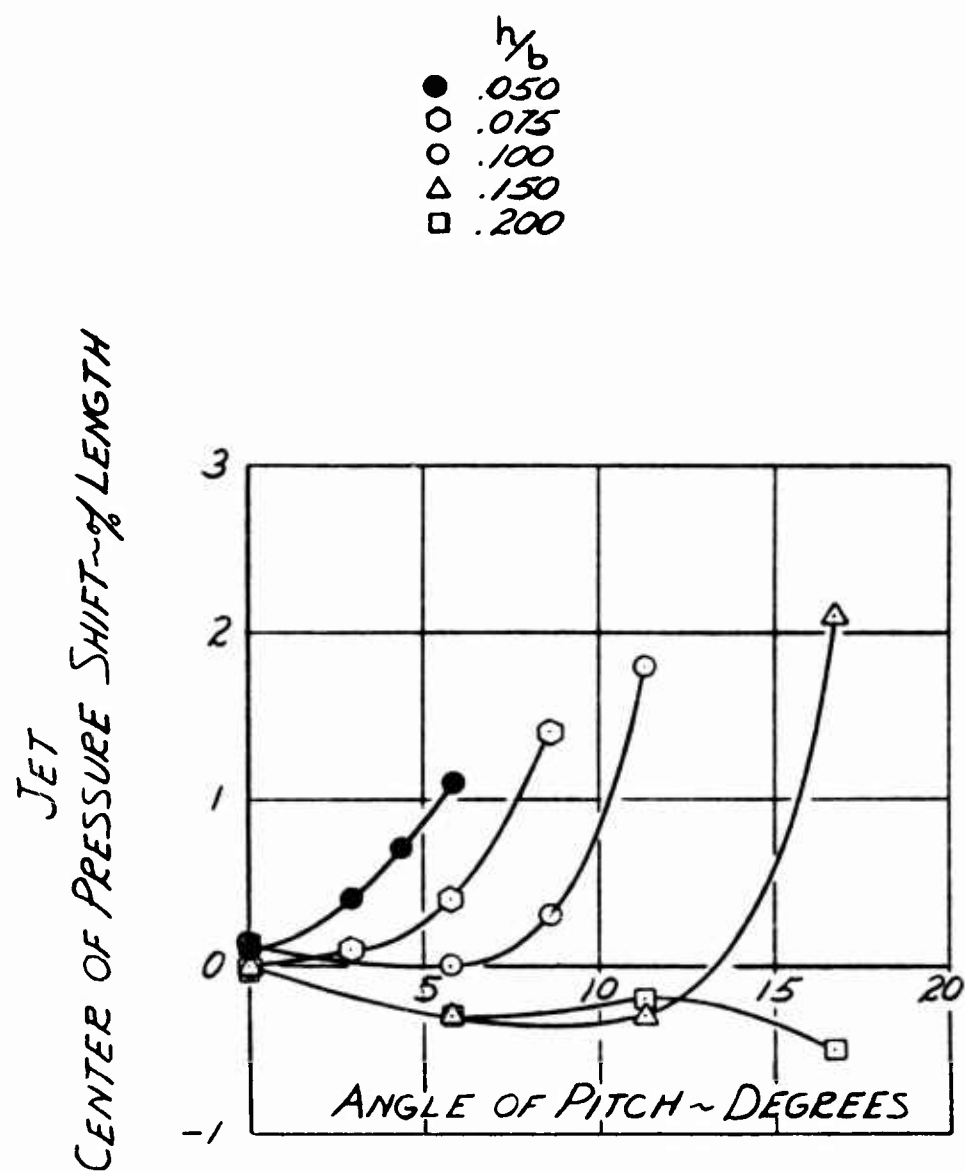
CORNER LOBE JET SEGMENTED MODEL Figure 27
BASE
CENTER OF PRESSURE SHIFT

h/b
● .050
⬡ .075
○ .100
△ .150
□ .200

46

Figure 28

CORNER LOBE JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT

47

Figure 29

CONCENTRIC JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

CONCENTRIC JET SEGMENTED MODEL
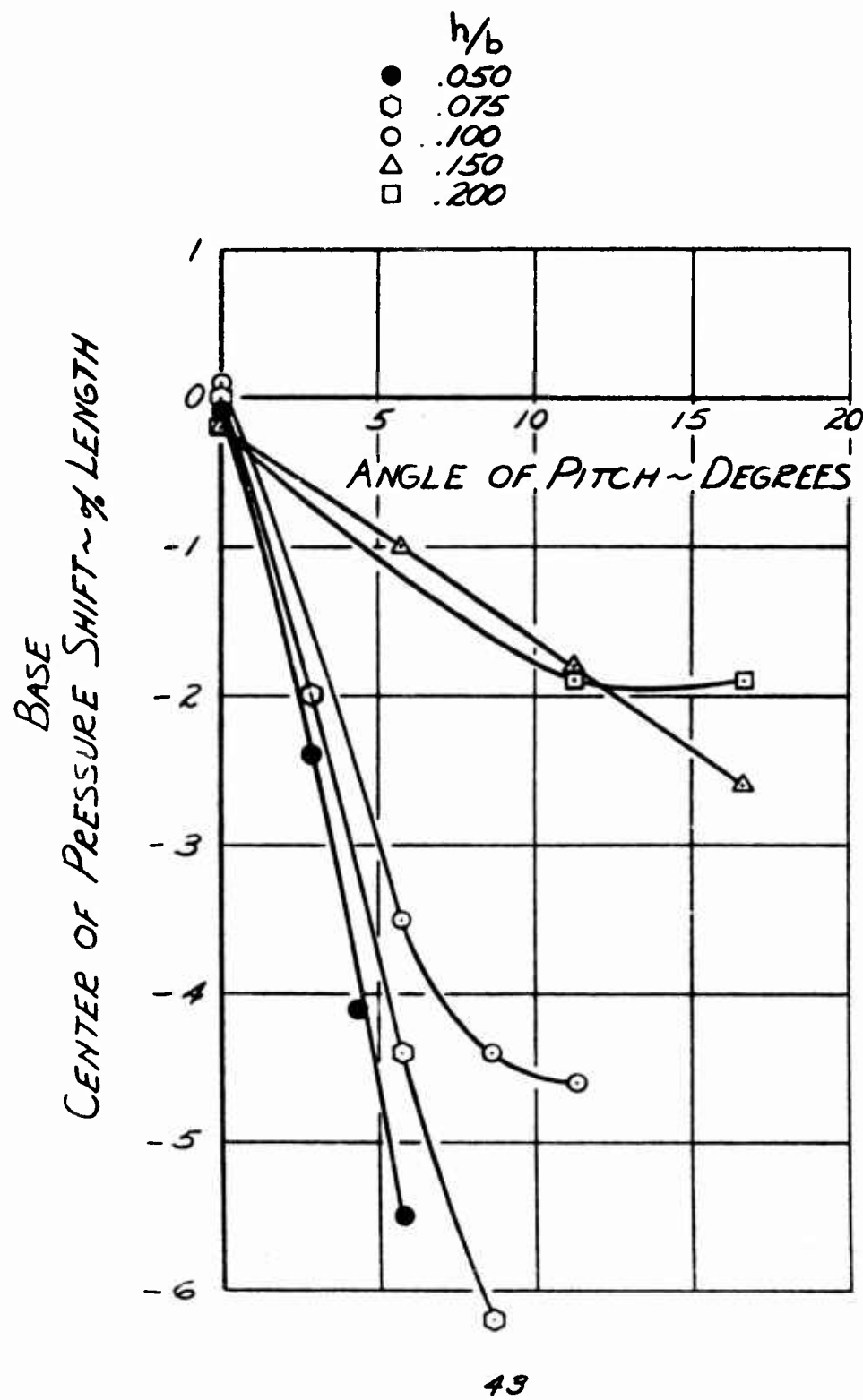BASE
CENTER OF PRESSURE SHIFT

Figure 30

49

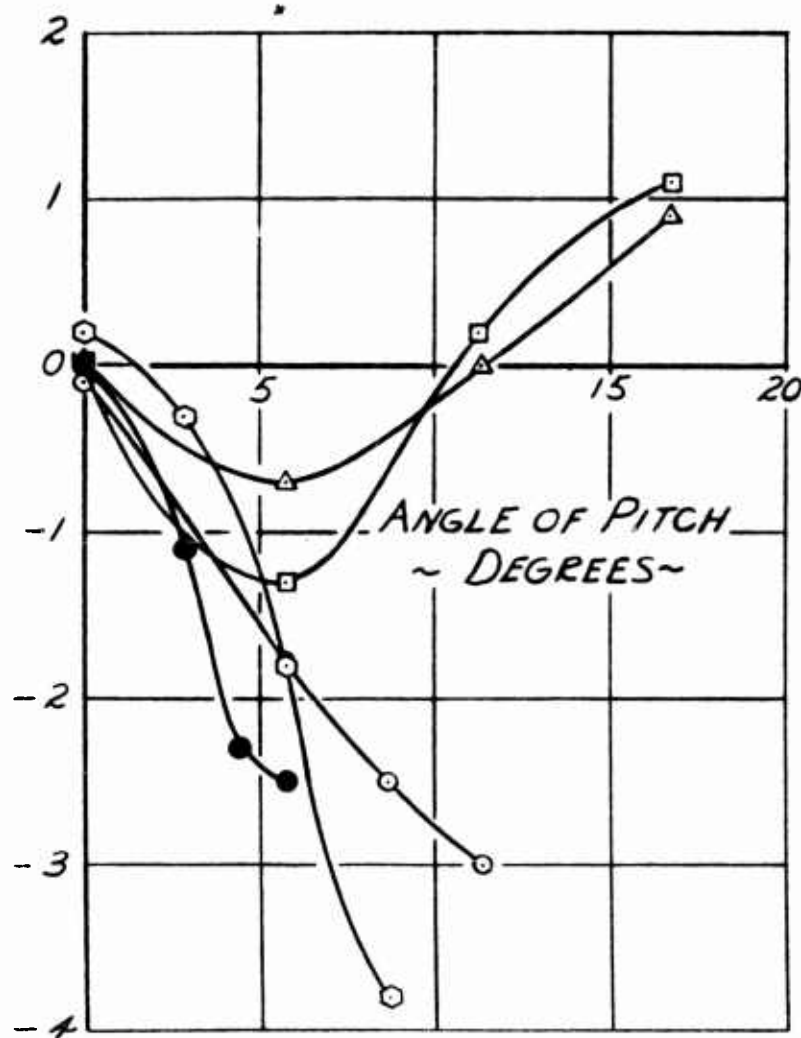Figure 31

CONCENTRIC JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT

Figure 32

EFFECT OF JET SEGMENTATION ON STATIC LONGITUDINAL HOVERING STABILITY

51
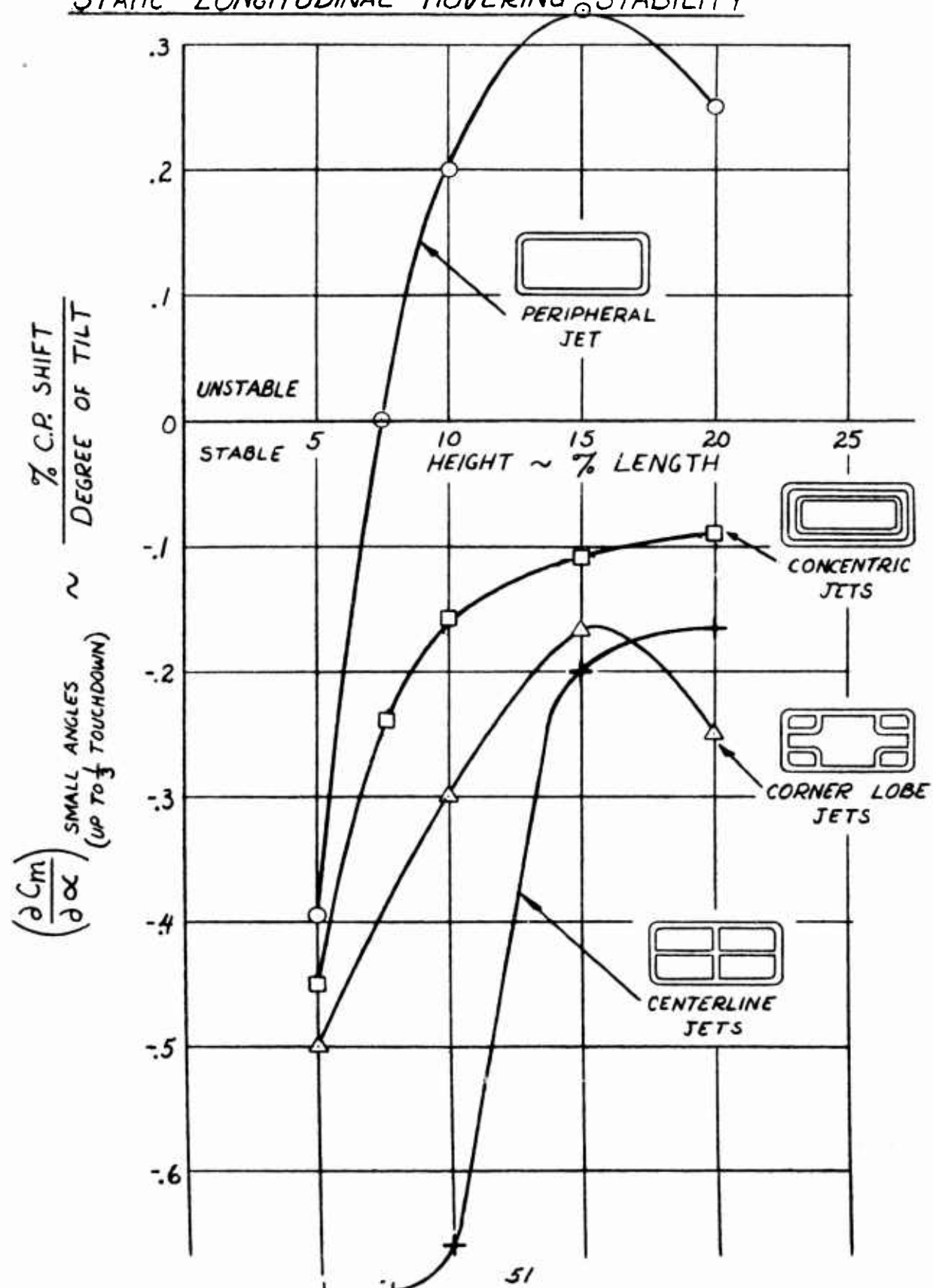
Figure 33

EFFECT OF JET SEGMENTATION
ON HEIGHT-PITCH ANGLE STABILITY BOUNDARIES

2.   Lateral Stability

a.   Simple Peripheral Jet Models

The base plus jet center of pressure shift of the vertical
peripheral jet model is shown in Figure 34. This configu-
ration is unstable in roll at small angles at all heights and
tends to become more unstable at large tilt angles. The
model was unstable in roll at heights where it was stable
in pitch. Since the model width is only half the model
length, the minimum physical height point was halved
in order to amount to the same percentage of characteristic
length as in the pitch case. This height = 5% w = 2.5% b still
produced an unstable slope. It would appear that long
narrow models have near two-dimensional flow patterns in
roll. Aeronutronic experiments (Reference 1) indicated
instability at all heights and angles for two-dimensional
flow.

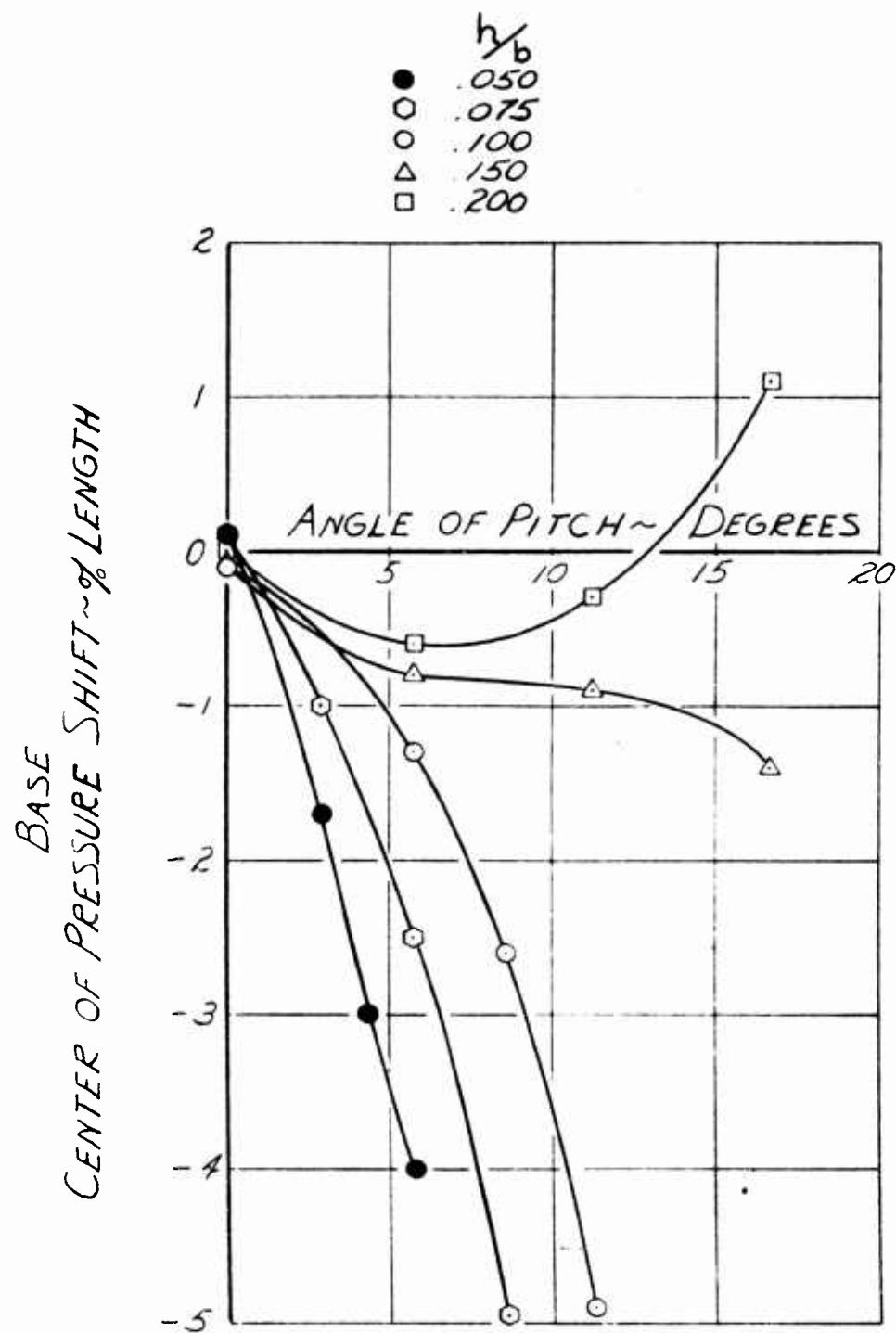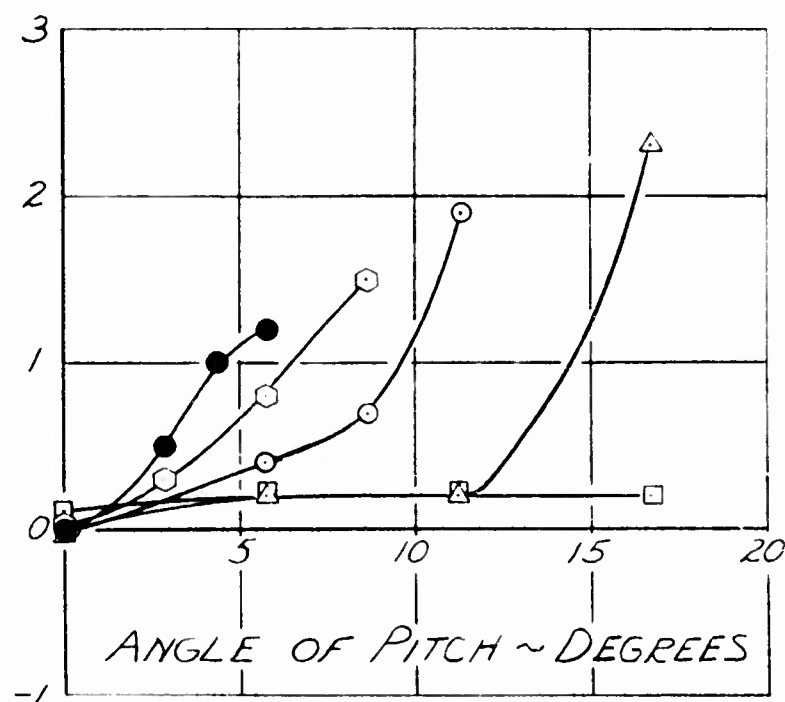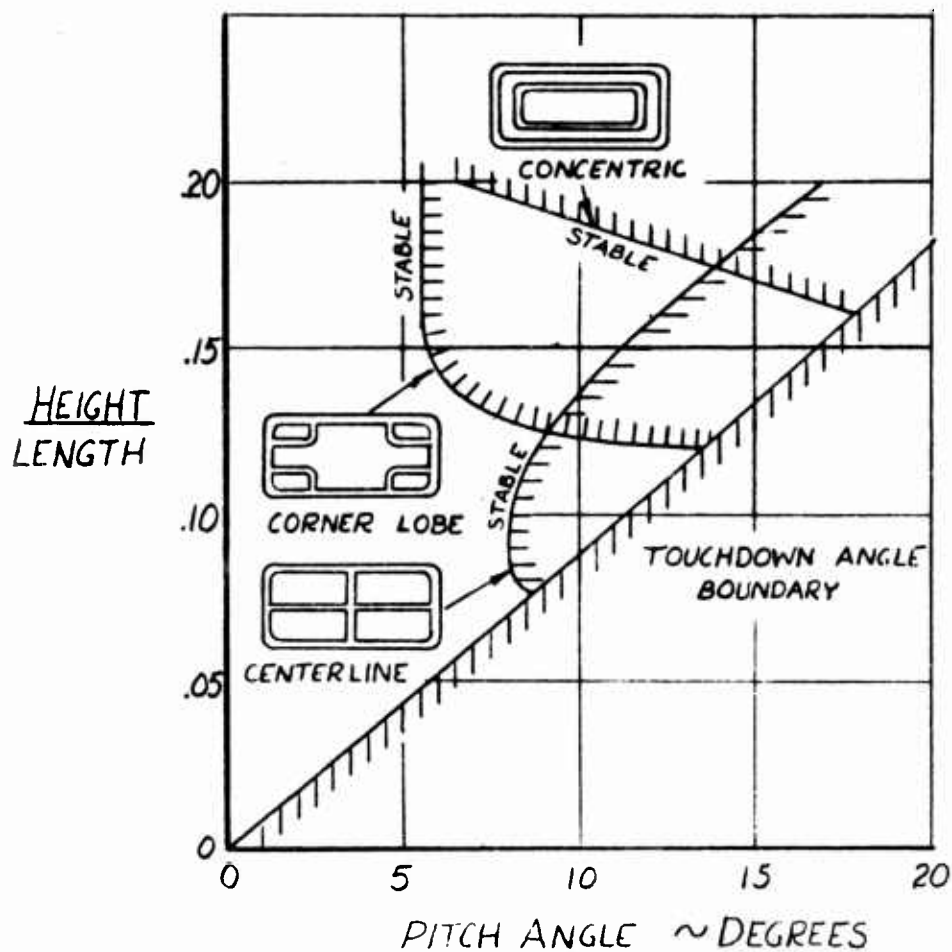The base center of pressure shift of Figure 35 is very
similar to the base + jet curves. There is, however, a
decrease of base instability at large tilt angles and low
heights. The jet contribution is small for all cases except
at tilt angles near touchdown at low heights as shown in
Figure 36.

The base + jet center of pressure shift of the 45° inclined
peripheral jet model as shown in Figure 37 is either
unstable or neutrally stable over the entire height range.
The degree of instability at both small and large tilt
angles is less for the 45° inclined jet than for the vertical
jet.

The base center of pressure shift as given in Figure 38
is very similar to the base + jet shift. The jet contribution
is small but becomes increasingly unstable as tilt angles
approach touchdown as shown in Figure 39.

The small angle lateral stability of the vertical and 45°
inclined jet are compared in Figure 40. The 45° inclined
jet is less unstable at low to moderate heights. There is
little difference at the larger height.

53

b. Effect of Base Shaping

The effect of shaping the base (in an effort to change the base pressure distribution under crossflow condition) was almost negligible as shown in Figure 41 and 42.

c. Skirted and Flap Segmented Models

The addition of a peripheral skirt alone did not change the instability in roll of the basic model to any extent as shown in Figure 43. The concentric flap was also not very helpful. The corner lobe flaps were somewhat more effective but still did not stabilize the model at either height. (15% and 20% of the width.) The single and double longitudinally running flaps stabilized the model at the lower height where they extended two-thirds of the way to the ground but failed to provide stability at the 20% height where they extended only half way to the ground.

The small angle stability slopes are compared for the various flap arrangements in Figure 44. In order of increasing improvement they are: concentric, corner lobe, single longitudinal, and double longitudinal. As mentioned before, the basic model instability in the lateral mode is more severe than in the longitudinal mode. It also appears to be more difficult to rectify the situation with segmenting flaps.

d. Jet Segmented Models

The base + jet center of pressure shift of the centerline jet segmented model is shown in Figure 45. Good small angle stability is available at all heights and holds up to 12 degrees of tilt angle. The model becomes unstable at large tilt angles at virtually all heights.

54

The base center of pressure shift shown in Figure 46 appears similar to the base + jet curves but retains a stable slope to higher angle-height combinations. The jet contribution is seen in Figure 47 to be responsible for the high angle instability of the base + jet.

The base + jet center of pressure shift of the corner lobe jet segmented model is shown in Figure 48. Small angle stability exists to a height of 20% of the width with instability occurring at higher heights. High angle instability is present at all height values. The base center of pressure shift curves presented in Figure 49 exhibit the same trends but have a lower degree of high angle instability. Figure 50 demonstrates the unstable contribution from the jets at tilt angles approaching touchdown.

The base + jet center of pressure shift of the concentric jet segmented model is shown by Figure 51 to exhibit almost neutral stability at all heights. The base contribution of Figure 52 is moderately stable at all heights and practically throughout the range of tilt angles. There is of course the usual decrease in magnitude of base stability contribution with increasing height. The jet contributions of Figure 53 are more unstable than for other configurations, even at small angles where neutral or slightly positive stability has been the rule. This effect was also present for the concentric jet in pitch. This could be expected since the two branches of the concentric arrangement will magnify the momentum choking on the low side.

The small angle stability of the jet segmented models is compared in Figure 54. The concentric model is slightly stable below 20% h/w and neutrally stable above this height. The corner lobe model is somewhat more stable below this crossover and slightly unstable at higher heights. The centerline jet segmented model is stable at all heights up through the maximum tested height of 40% of the width!

The height-roll angle stability boundaries are compared
in Figure 55. The concentric and corner lobe boundaries
are very similar and the centerline jet segmented model
shows a clear superiority. It should be emphasized that
even the centerline jet segmented model is unstable at
very large tilt angles.

Figure 34

VERTICAL PERIPHERAL JET MODEL
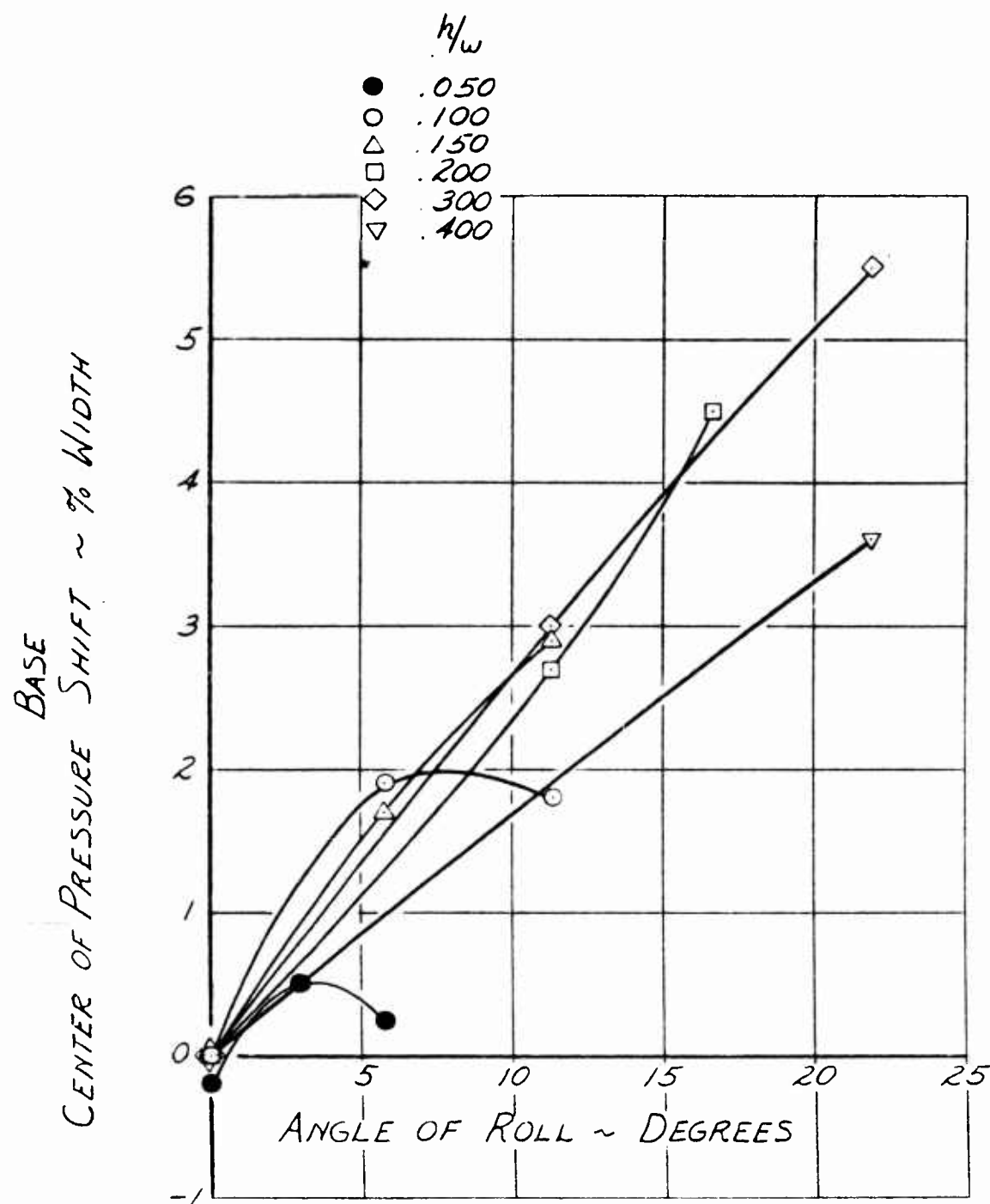## BASE PLUS JET
CENTER OF PRESSURE SHIFT

57
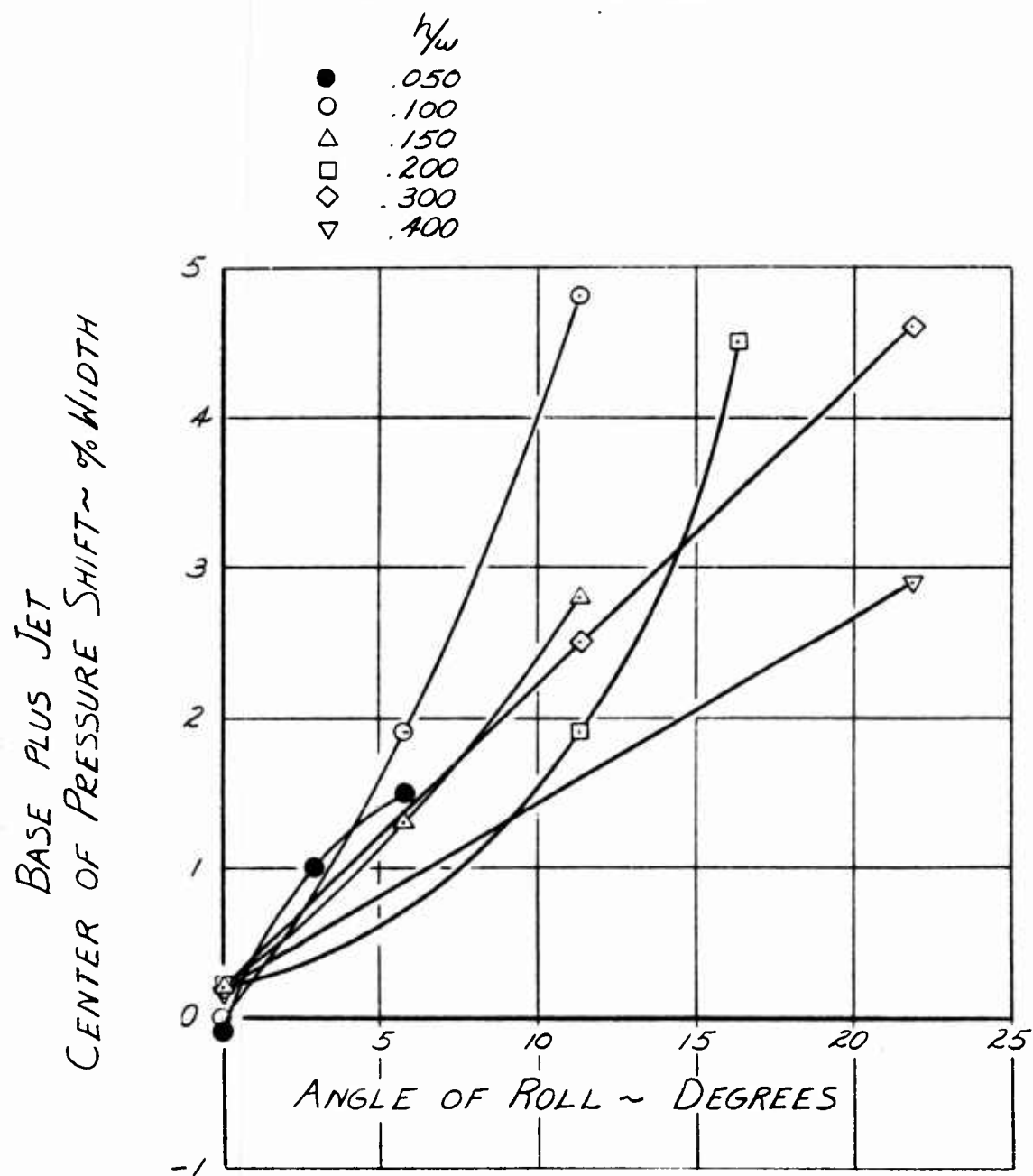
Figure 35

VERTICAL PERIPHERAL JET MODEL
BASE
CENTER OF PRESSURE SHIFT
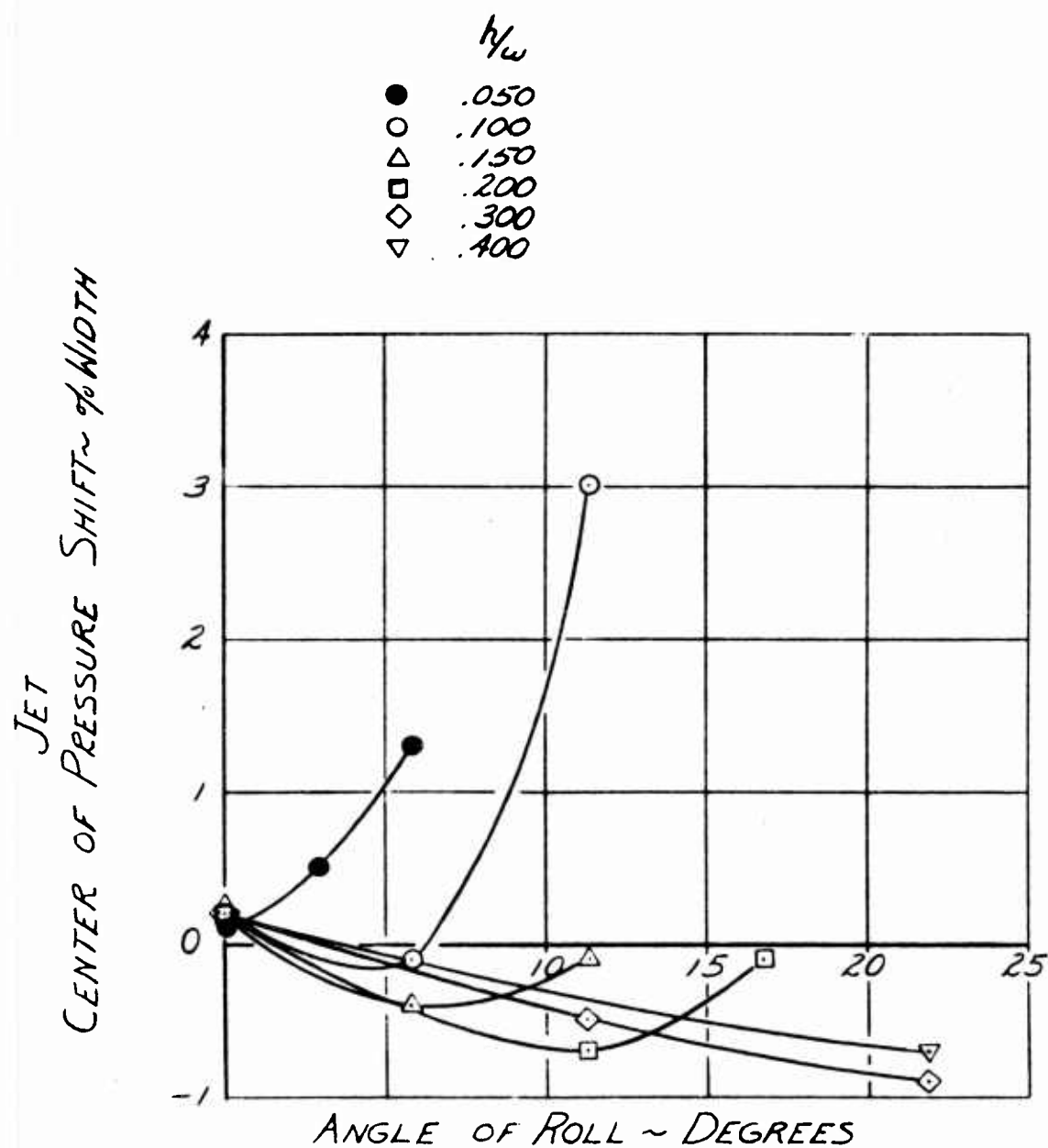
58

VERTICAL PERIPHERAL JET MODEL
JET
CENTER OF PRESSURE SHIFT

Figure 36

59

Figure 37

45° INCLINED PERIPHERAL JET MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 38

45° INCLINED PERIPHERAL JET MODEL
BASE
CENTER OF PRESSURE SHIFT

Figure 39
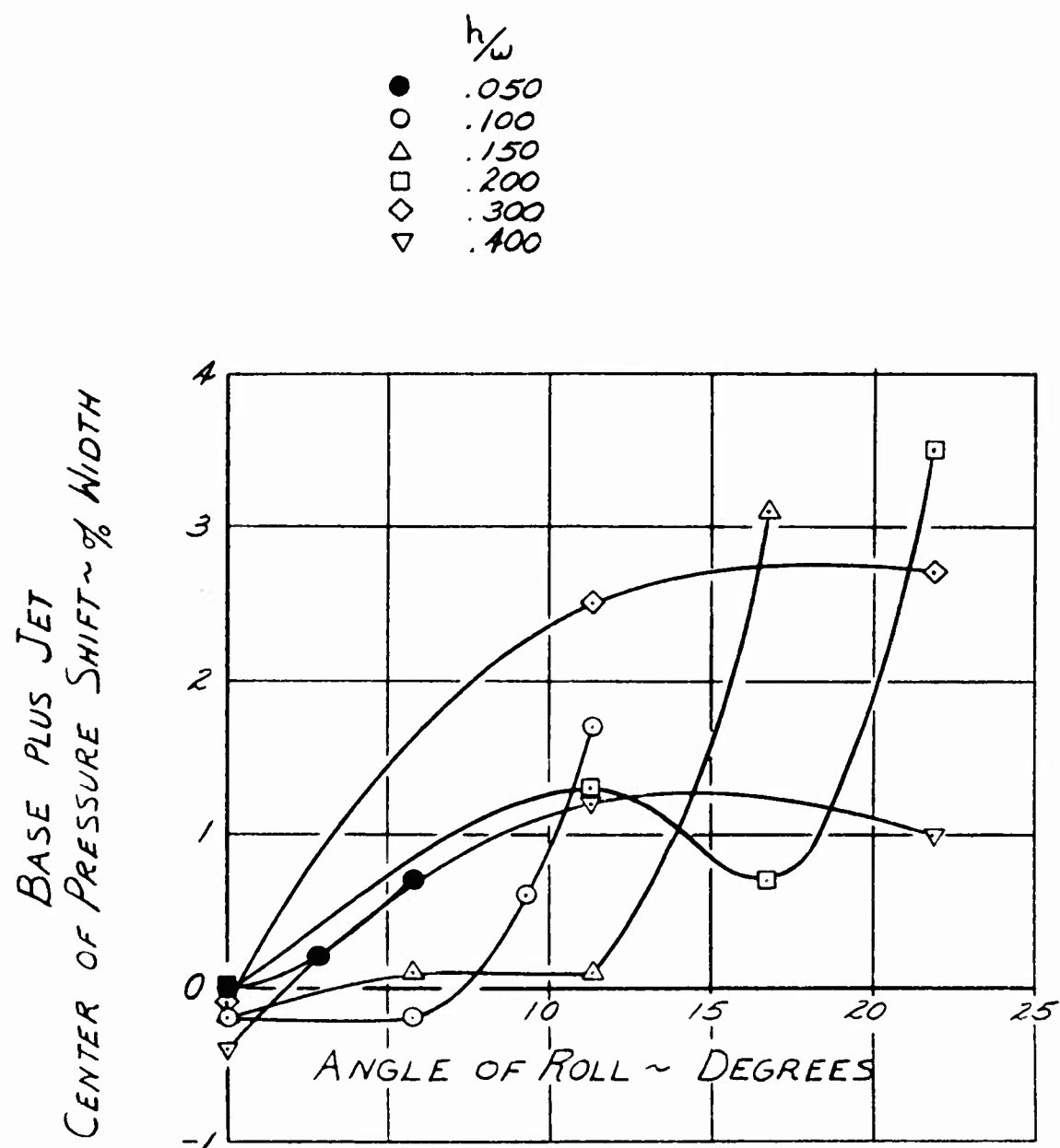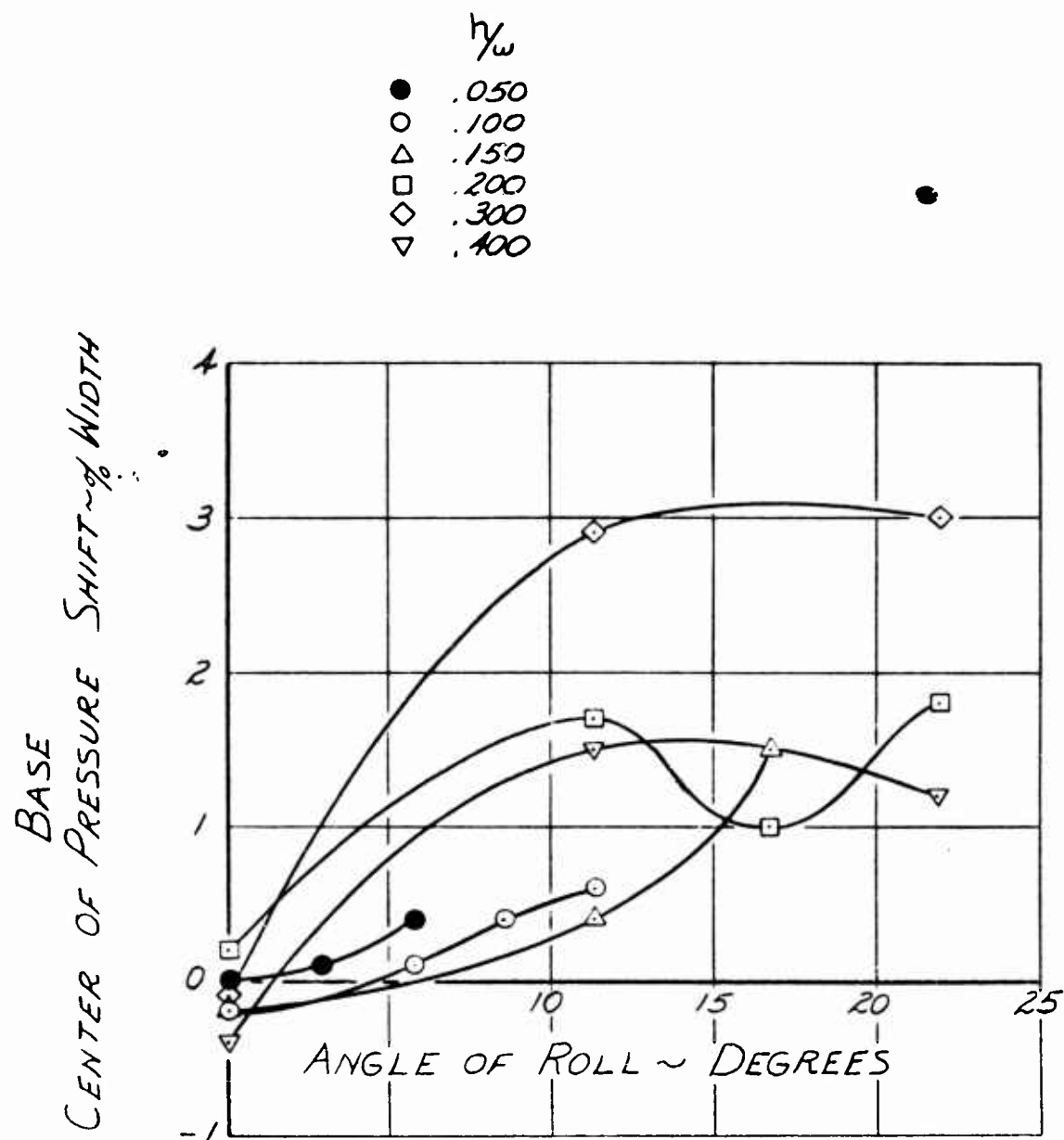
45° INCLINED PERIPHERAL JET MODEL
JET
CENTER OF PRESSURE SHIFT

Figure 40

STATIC LATERAL HOVERING STABILITY

VERTICAL vs. 45° INCLINED JET
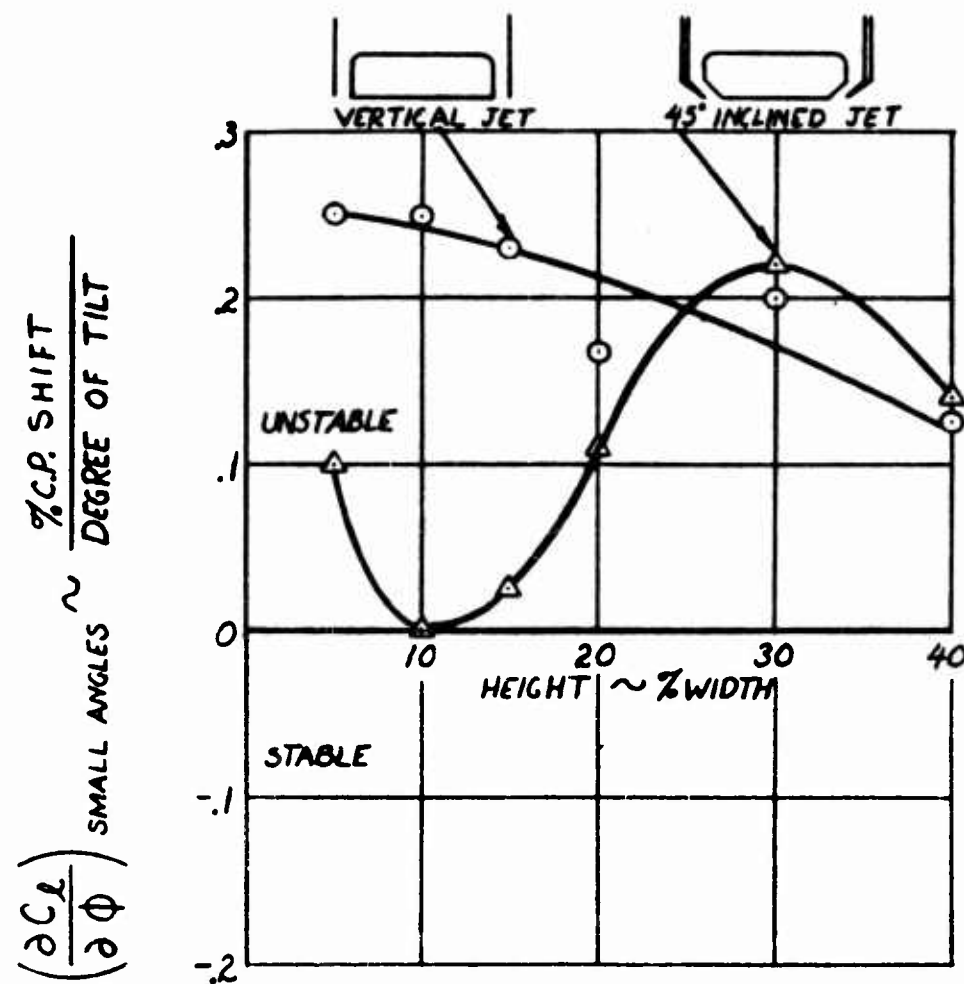
Figure 41
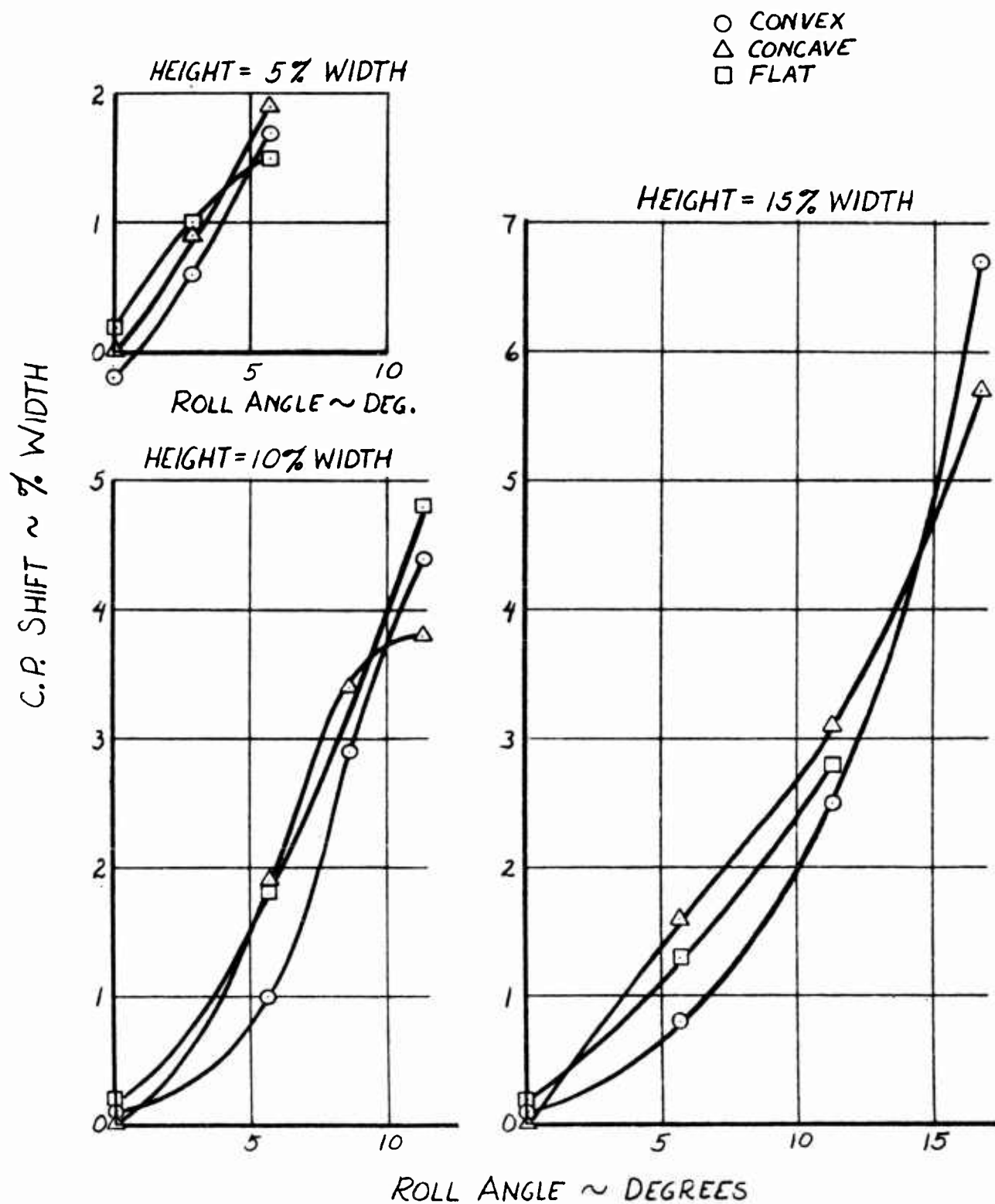
EFFECT OF BASE SHAPING ON BASE PLUS JET
CENTER OF PRESSURE SHIFT

○ CONVEX
△ CONCAVE
□ FLAT

HEIGHT = 5% WIDTH

HEIGHT = 15% WIDTH

HEIGHT = 10% WIDTH

C.P. SHIFT ~ % WIDTH

ROLL ANGLE ~ DEG.

ROLL ANGLE ~ DEGREES

64

CENTER OF PRESSURE SHIFT
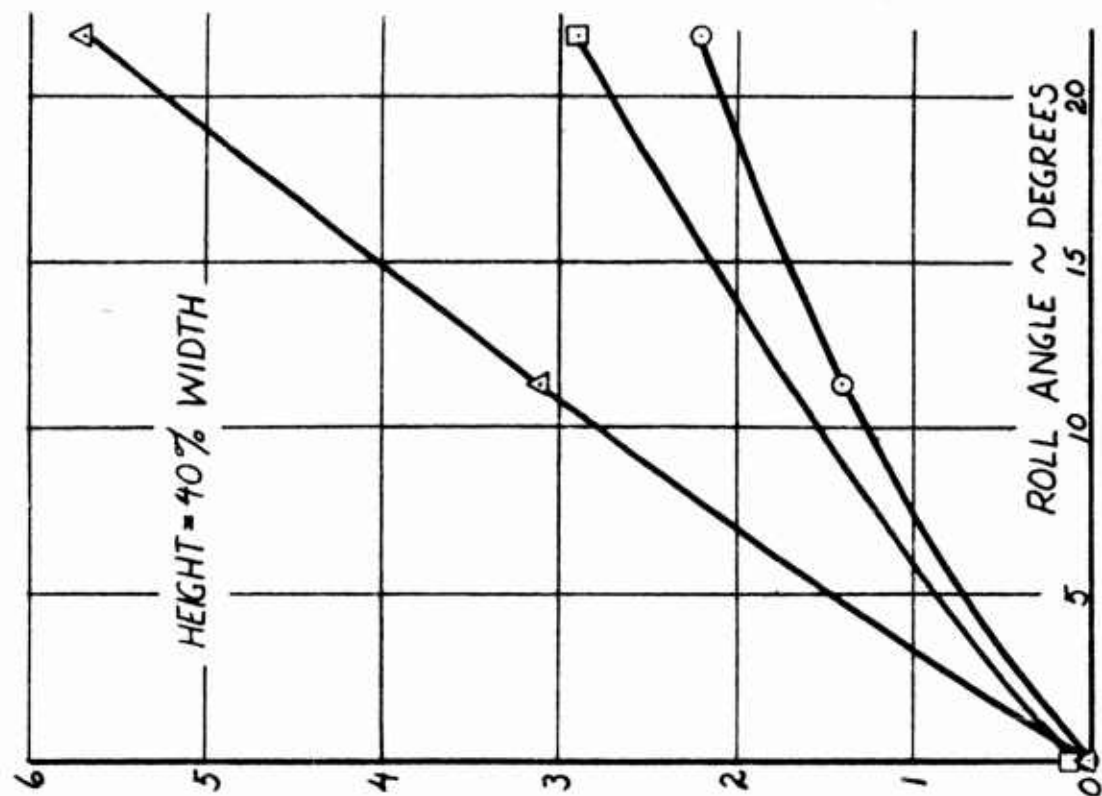
Figure 42

EFFECT OF SKIRT AND FLAPS
ON BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 43

NOTE:
SKIRT & FLAPS
5% OF LENGTH

O   NO SKIRT

$\frac{h}{w} = .15$

C.P. SHIFT ~ % WIDTH

ANGLE OF ROLL ~ DEG.

$\frac{h}{w} = .20$

△   WITH SKIRT

ANGLE OF ROLL ~ DEG.

66
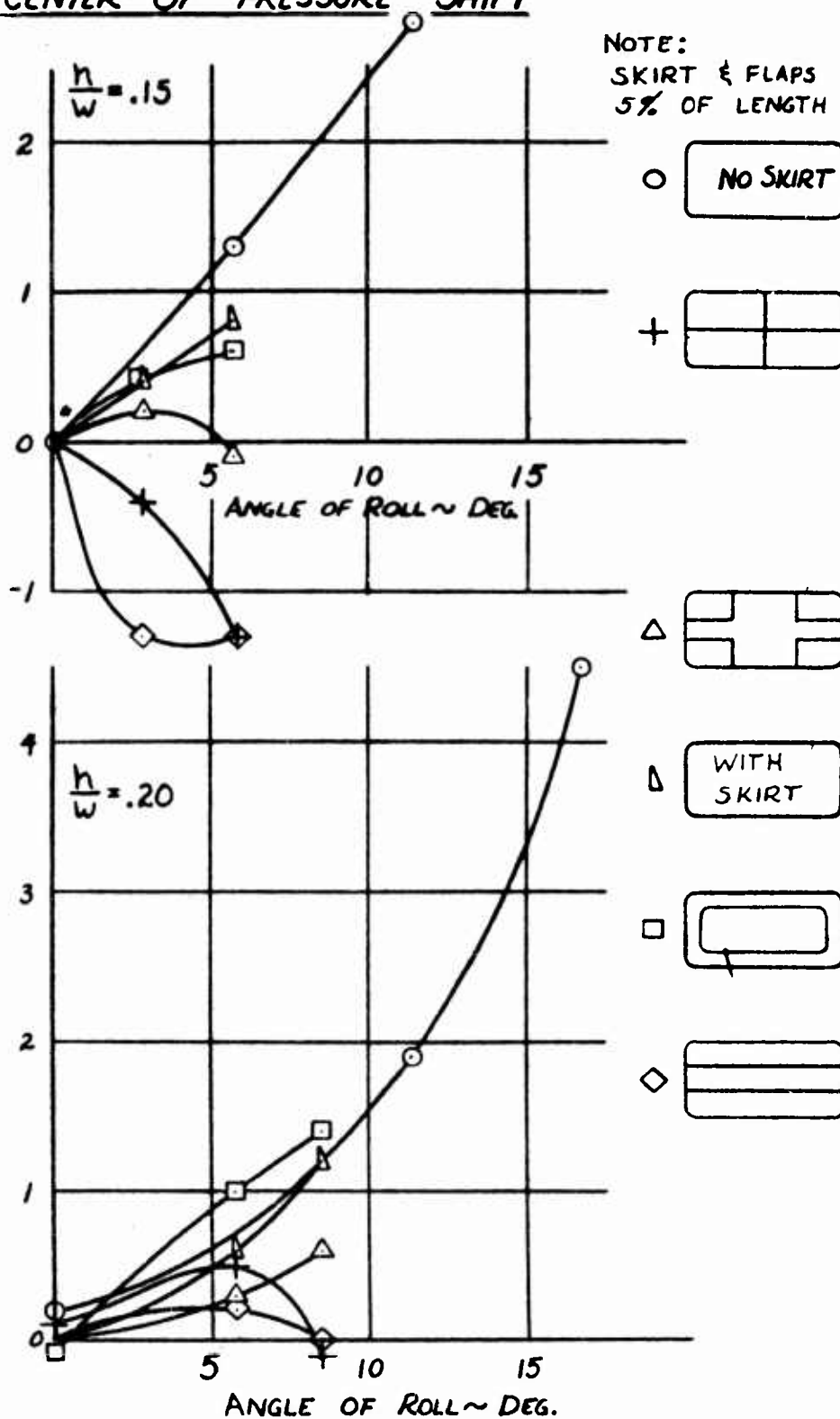
Figure 44

EFFECT OF 5% LENGTH SKIRT AND FLAPS
ON STATIC LATERAL HOVERING STABILITY
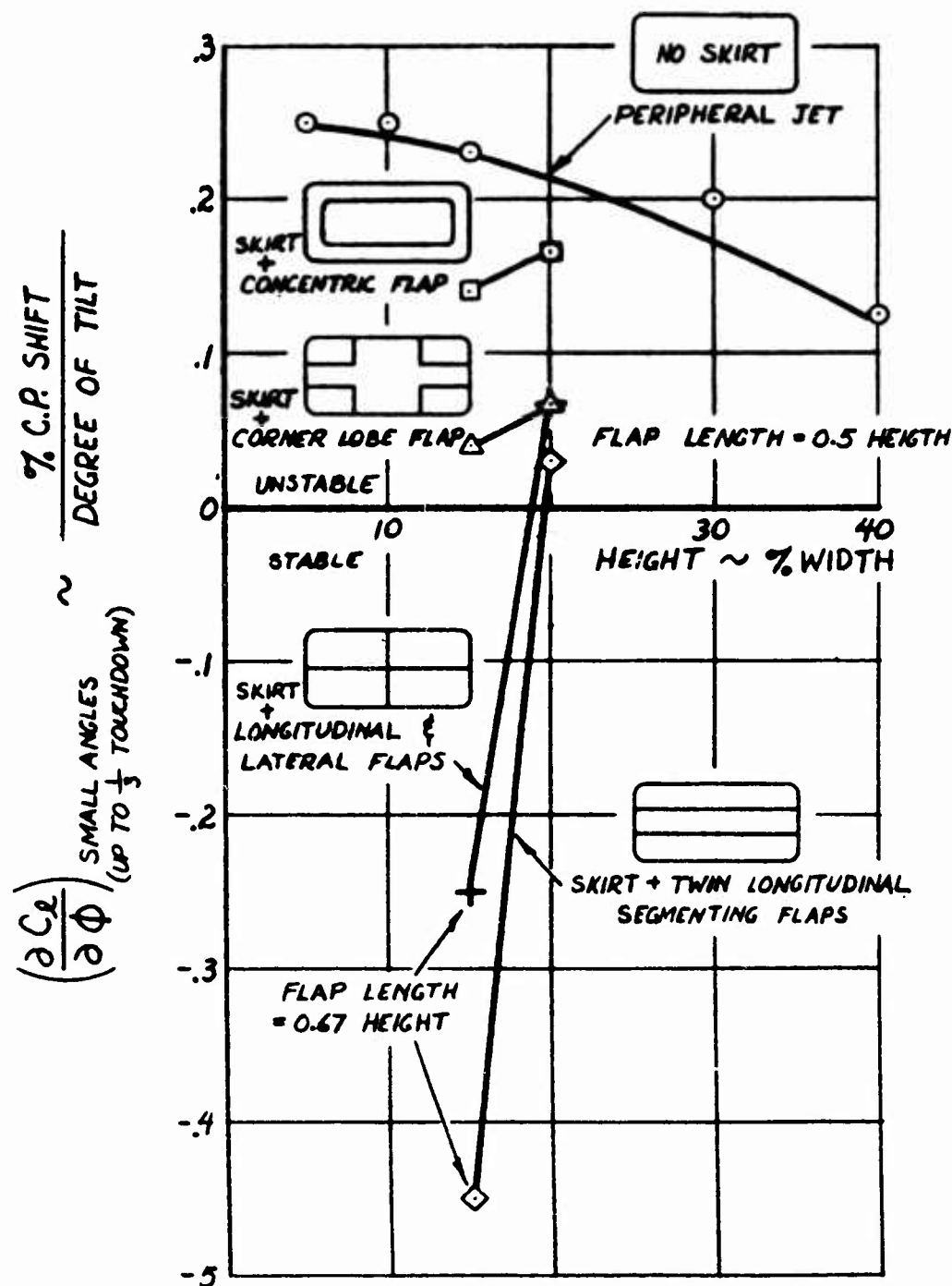
Figure 45

CENTERLINE JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 46

CENTERLINE JET SEGMENTED MODEL
BASE
CENTER OF PRESSURE SHIFT

Figure 47

CENTERLINE JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT

70

Figure 48

CORNER LOBE JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

71

Figure 49

CORNER LOBE JET SEGMENTED MODEL
BASE
CENTER OF PRESSURE SHIFT

Figure 50

CORNER LOBE JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT

Figure 51

CONCENTRIC JET SEGMENTED MODEL
BASE PLUS JET
CENTER OF PRESSURE SHIFT

Figure 52
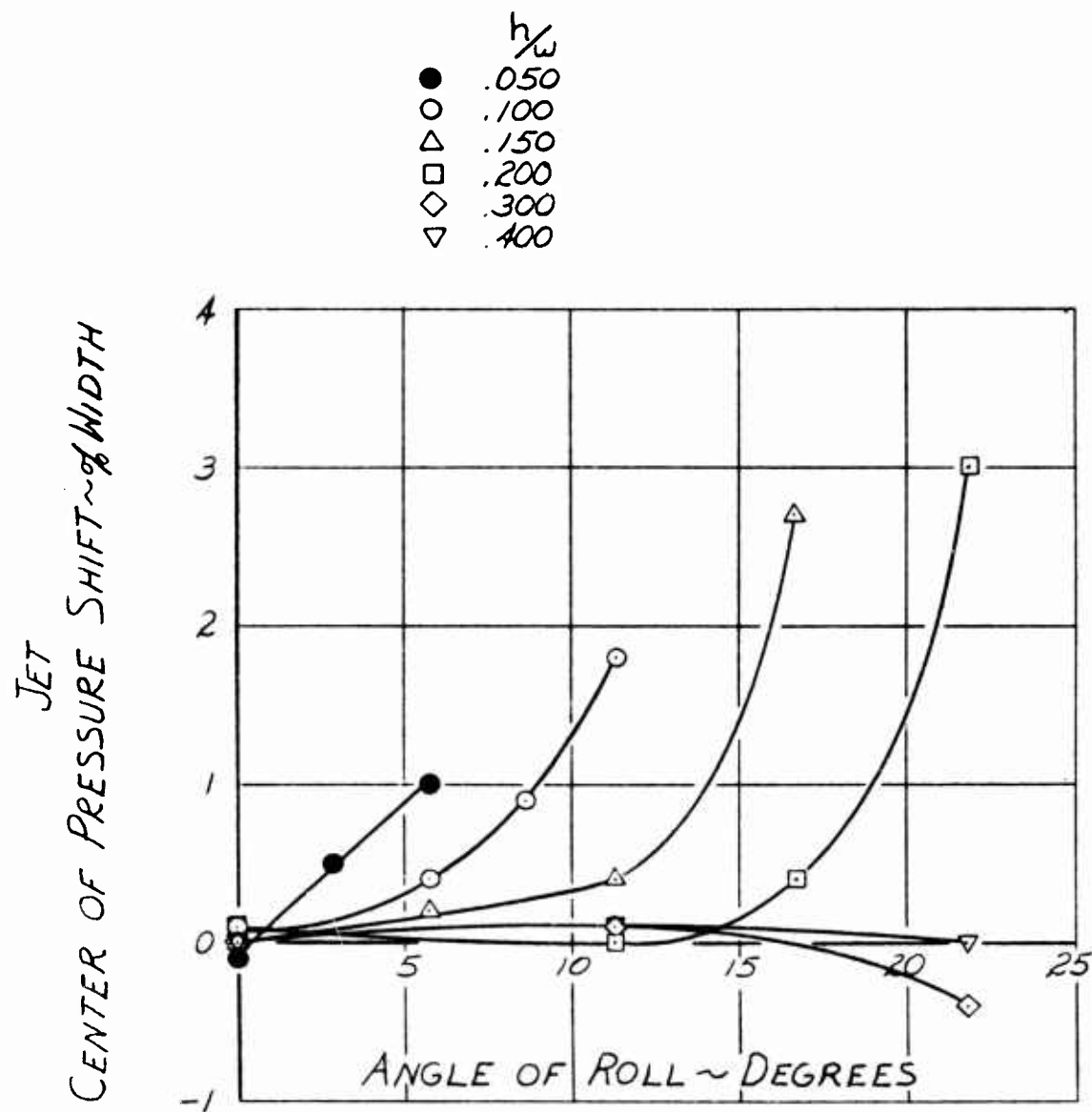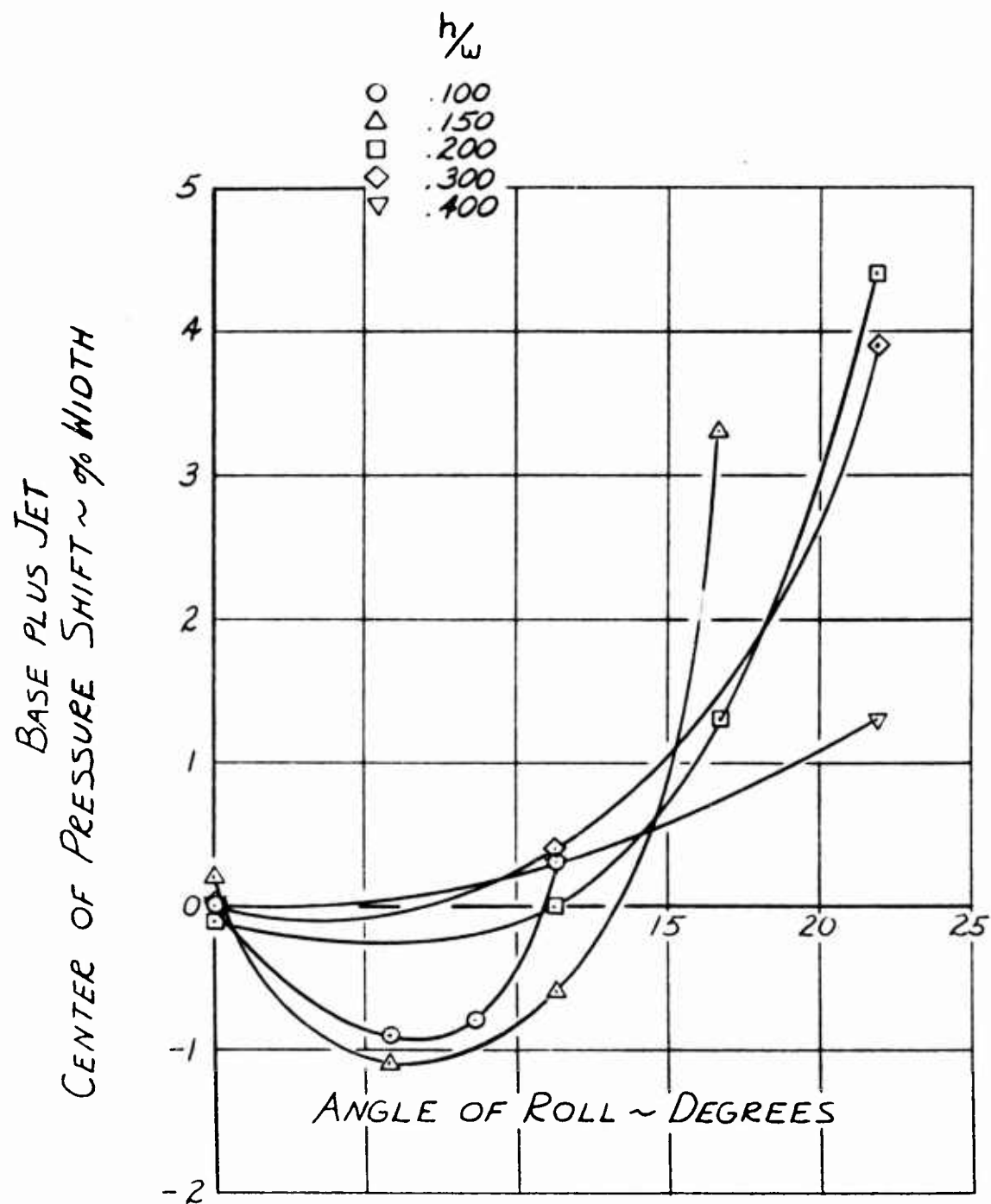
CONCENTRIC JET SEGMENTED MODEL
BASE
CENTER OF PRESSURE SHIFT

● .050
○ .100
△ .150
□ .200
◇ .300
▽ .400

75
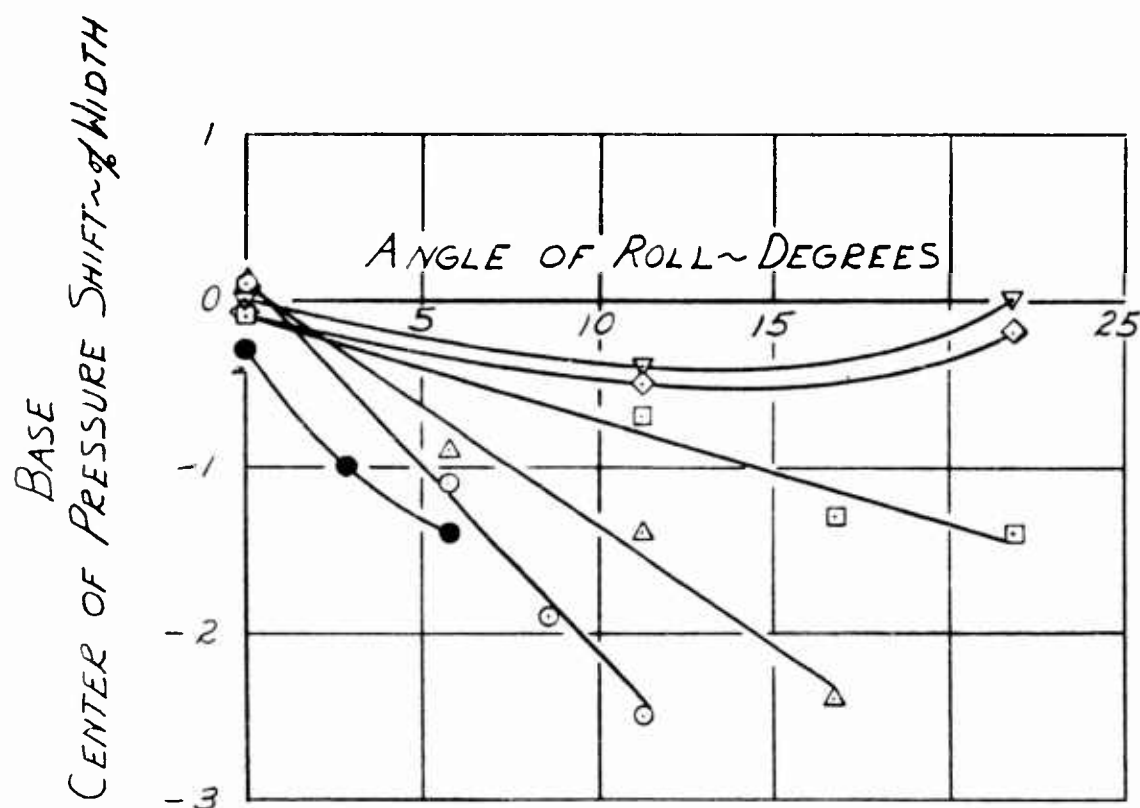
Figure 53

CONCENTRIC JET SEGMENTED MODEL
JET
CENTER OF PRESSURE SHIFT
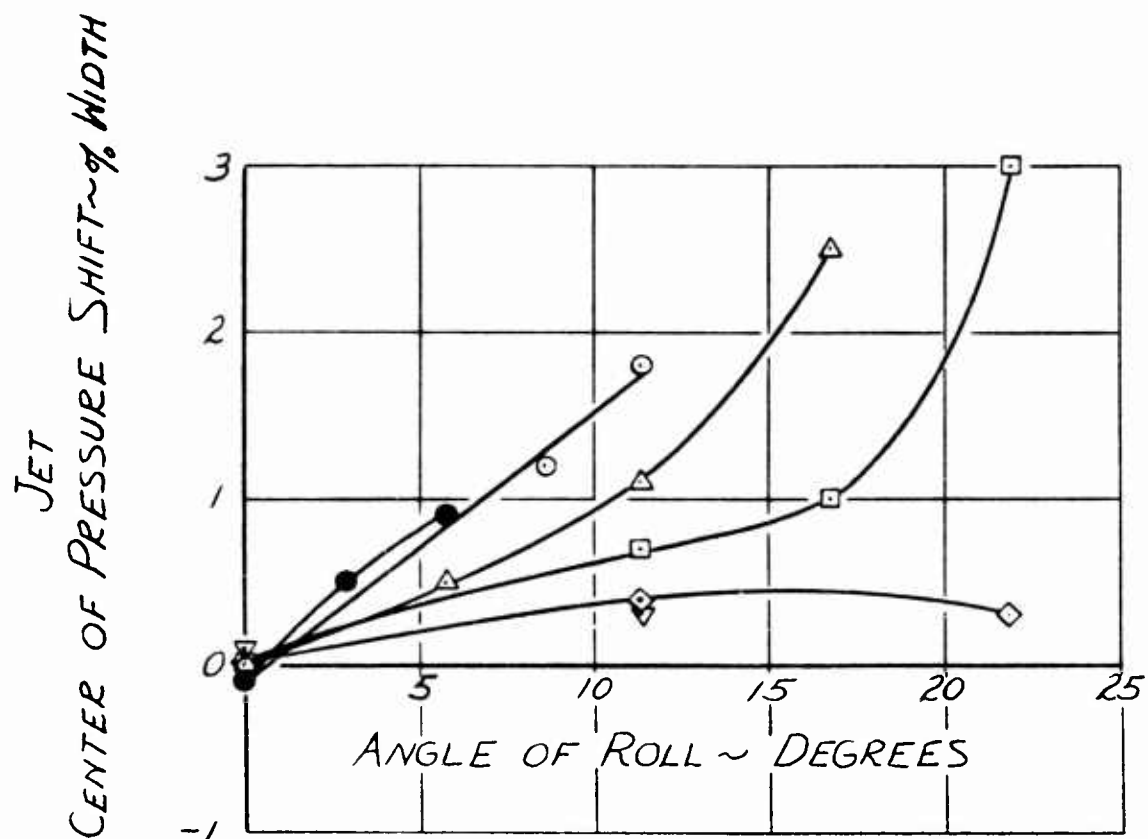
Figure 54

EFFECT OF JET SEGMENTATION
ON STATIC LATERAL HOVERING STABILITY

Figure 55
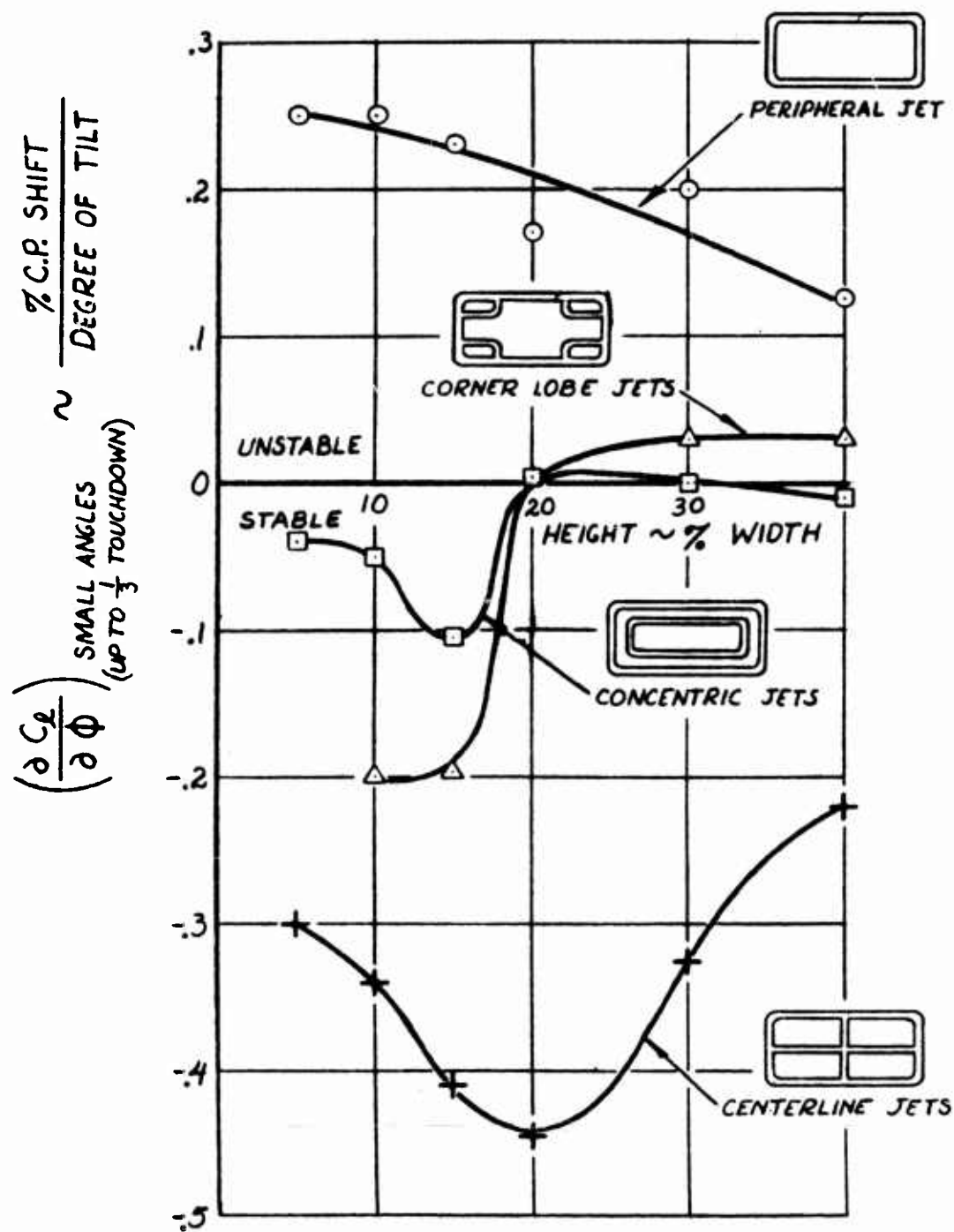
EFFECT OF JET SEGMENTATION
ON HEIGHT-ROLL ANGLE STABILITY BOUNDARIES
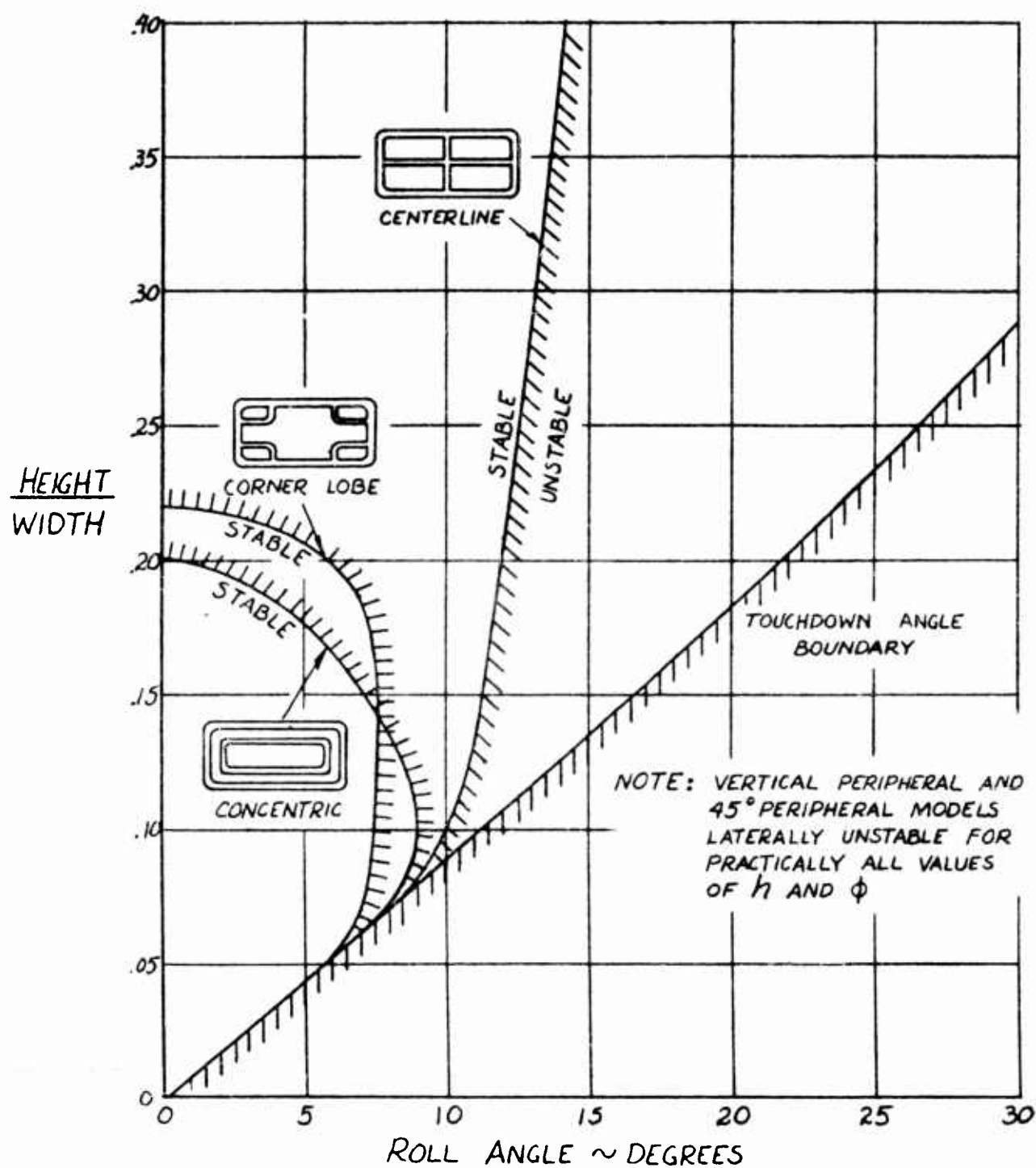
3. Qualifications of the Stability Results

a. Response of the Flow Supply

It should be remembered that the results presented here
are for a near ideal flow impeller and internal aero-
dynamic system. The Chicago Airfoil Centrifugal Fan
output was not affected by model tilt. The internal
aerodynamics were simple such that no unsymmetry in
total head occurred due to tilt. The average total head
on the low and high end of the models were within one-
half of 1% of each other throughout the range of pitch
and roll angles. This might not necessarily hold true
of an actual air-cushion vehicle with an axial flow im-
peller and internal aerodynamics which are compromised
because of space limitations.

b. Possible Contributions Not Measured in the Tests

The air loads which were integrated to provide the lift
and moments in this work consisted of the load normal
to the base and the reactions along the jets. Theoretical
and experimental work on plenum chambers by Hunt of
English Electric Company (Reference 7) has revealed a
chord force in the plane of the base which can be appreciable
for plenum chambers at large tilt angles. Unpublished
recent experiments at Aeronutronic with a six-component
force balance have indicated that although the chord force
may be 10% of the normal force for a plenum chamber it
does not exceed 2% of the normal force for a peripheral jet
configuration. This was found to hold true for both simple
and jet segmented models. Thus, it would appear that
little, if any, inaccuracy has been introduced by the
pressure integration method employed in these tests.
It should be remembered that the moment center in these
experiments was in the plane of the base. The center of
gravity of any vehicle will be somewhat higher. Thus,
chord forces, if present, will have an appreciable arm.

79

4. **Performance Aspects**

a. Effect of Tilt of Lift

The stability data which has been presented was obtained with the model pitch axis at a fixed distance above the ground. In practice, the vehicle will lose lift and thus height as it tilts. It is therefore of interest to examine the rate at which the lift decreases with tilt angle.

The ratio of the lift (perpendicular to the ground) to the lift with model level was found for the vertical peripheral jet model to fall from 1.6 to 2.5% per degree of tilt. The lift loss is near the lower figure at very low and very high heights and near the high figure at intermediate heights. The range of values of lift loss per degree tilt is identical for the pitch and roll case.

The effect of several flap configurations on the lift loss at a base h/b = 0.10 was examined. The concentric flap and twin longitudinal flap have the same rate of lift loss as the plain configuration. The corner lobe and centerline flap configurations reduce the rate of lift loss from 2.5%/deg to 2.0%/deg in both pitch and roll.

The effect of peripheral jet inclination and jet segmentation of the base on the lift loss at a base h/b = 0.10 was also investigated. The basic vertical jet had a loss rate of 2.5% per degree, the 45° inclined peripheral jet and the concentric segmented jet models had a loss of 1.3% per degree, and the corner lobe and centerline jet segmented model had a loss of 0.4% per degree, in pitch. In roll, the curves are not as linear, but in general the rate varies from 1.0% per degree to 2.5% per degree. Increasing h/b to 0.15 or h/w to 0.30 reduces the loss rate in pitch and roll to 0.85 to 1.8%/deg.

b. Cost of Stabilization

Where special techniques of stabilization require
power, it is of interest to determine the cost in
performance.

The hovering performance of air-cushion vehicles is
generally expressed as a power savings due to ground
effect. This ground effect power factor G is the ratio
of $\frac{L}{P}\sqrt{\frac{L}{S}}$ of an ideal ducted rotor operating out of

ground effect to that of the air-cushion vehicle in ground
effect.

There are three possible
ways to express the gain
in hovering performance
of an air-cushion vehicle
compared to the ideal
rotor out of ground effect
once the value of G is given.

$$G = \frac{\dfrac{L^{3/2}}{P(S)^{1/2}} \quad \text{ideal}}{\dfrac{L^{3/2}}{P(S)^{1/2}} \quad \text{air-cushion}}$$

(1) Same Lift and Area

$$\frac{P_{AC}}{P_i} = G$$

(2) Same Power and Area

$$\frac{L_{AC}}{L_i} = \left(\frac{1}{G}\right)^{2/3}$$

(3) Same Power
and Lift

$$\frac{S_{AC}}{S_i} = G^2$$

It should be noted that the results of comparison of G for
the various configurations presented in the following
paragraphs should not be generalized as the cost for
hovering stabilization for all air-cushion vehicles. The
configurations tested were compromised (with forward
flight considerations in mind) away from optimum hovering
values of jet thickness and angle.* It is probable that the
cost of hovering stabilization might come out differently

* Jets were thinner and less inclined than optimum.

81

if one started with an optimum hovering configuration.
The results presented here are believed of more practical
interest, however, since the goal of air-cushion develop-
ment effort is to produce a transportation system, not a
hovering system. Considerable additional analysis work
would be required to enable prediction of hovering per-
formance and stability of a broad enough family of jet
segmented planforms to permit analytical optimization.

A comparison of the experimental results obtained for
the vertical peripheral jet with predicted results using
the two-dimensional annular jet performance data and
method of Reference 8 are presented in Figure 56. The
agreement is quite good.

The vertical peripheral jet model requires only 30% of
the ideal rotor power out of ground effect at $h1/S = 0.14$.
Above $h1/S = 0.63$ more power is required than for the
ideal rotor out of ground effect. It should be remembered
that this is exit power and does not include any internal
flow losses. Actual air-cushion vehicles would become
inferior to the ideal rotor at even lower values of $h1/S$.

The skirted model data was also plotted vs. $h1/S$ where h
was measured to the base, not the bottom of the skirt.
Figure 56 shows that with the base at $h1/S = 0.42$, the
G was identical as the unskirted version at $h1/S = 0.14$.
The clearance to the bottom of the skirt $h'1/S$ was 0.14
when $h1/S$ was 0.42. This result indicates that at low
skirt clearances the performance is as good as if the base
were as low as the bottom of the skirt. At the higher
height $h1/S = 0.56$, $h'1/S = 0.28$ the performance is close
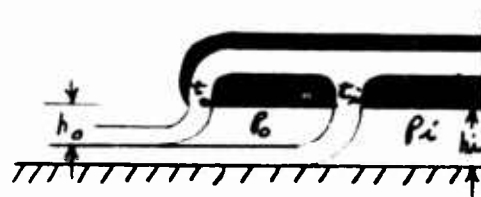to, but not quite as good as if the base were at the bottom
of the skirt.

The G factors for the three types of jet segmented models
are compared to the vertical peripheral jet model in
Figure 57. The differences are very slight at $h1/S = 0.3$.

At higher values of hl/S, the corner lobe and centerline
jet segmented models are inferior to the vertical peripheral
jet model and become inferior to the ideal rotor out of
ground effect at hl/S = 0.58.   The concentric vertical jet
model is superior to the vertical peripheral jet model
at all values of hl/S and remains superior to the ideal
ducted rotor out of ground effect up to hl/S = 0.73.   It
was disappointing that the concentric jet did not do a
better job of lateral stabilization, since its performance
is superior to the other configurations.   The penalty in
$L^{3/2}/\mathcal{P}$ for both the centerline and corner lobe jet
segmented models was 8% at hl/S = 0.6 and only 4% at
hl/S = 1.0.   The concentric jet exhibited an improvement
in $L^{3/2}/\mathcal{P}$ of 8% at hl/S = 0.6 and 11.5% at hl/S = 1.0.

Comparative performance and stability of the vertical
peripheral jet model and the centerline jet segmented
model at two heights is presented in Figure 58.   The
centerline jet segmented model provided superior sta-
bility at the higher heights and the performance penalty
was not severe.

The performance results for the concentric jet model were
unusual enough to raise suspicion as to the experimental
validity.   The G values of the concentric jet model were
more favorable than those for the basic peripheral jet.

A simple concentric theory
was developed by the author
to allow lift and power
estimations based on the
two-dimensional data and
methods previously men-
tioned.   The outer jet was
assumed to flow out over
the inner jet.   The value
of p_o was based on t_o/h_o where $h_o = h_i - t_i$.   The value
for $p_i = p_o + \Delta p_i$ where Δp_i was based on t_i/h_i.   The

83

inner jet was assumed to face a back pressure of
$(p_o + p_i)/2$ and the outer jet was assumed to face a
back pressure of $p_o/2$. Both jets were assumed to be
at the same total pressure as in the experiment.

This simple theory at $hl/S = 0.56$ predicted 41% more
lift for the concentric than for the simple peripheral jet,
whereas the experiment produced 37% more. The theory
predicted 45% more power for the concentric than for
the basic, whereas the experiment produced 49% more
power. The theoretical ratio of $L^{3/2}/P$ was 15%
larger for the concentric according to the simple theory,
whereas it was only 8% larger in the experiment. At
least the theory confirmed that the hovering performance
of the simple non-optimum peripheral jet could be
improved by increasing the jet thickness even with a
concentric arrangement as indicated by the experiment.
One should not infer from this, however, that optimum
concentric jets are superior in performance to optimum
simple peripheral jets. In fact, for the case of near
optimum thickness, the pure peripheral jet will be superior
in hovering performance to the concentric arrangement.
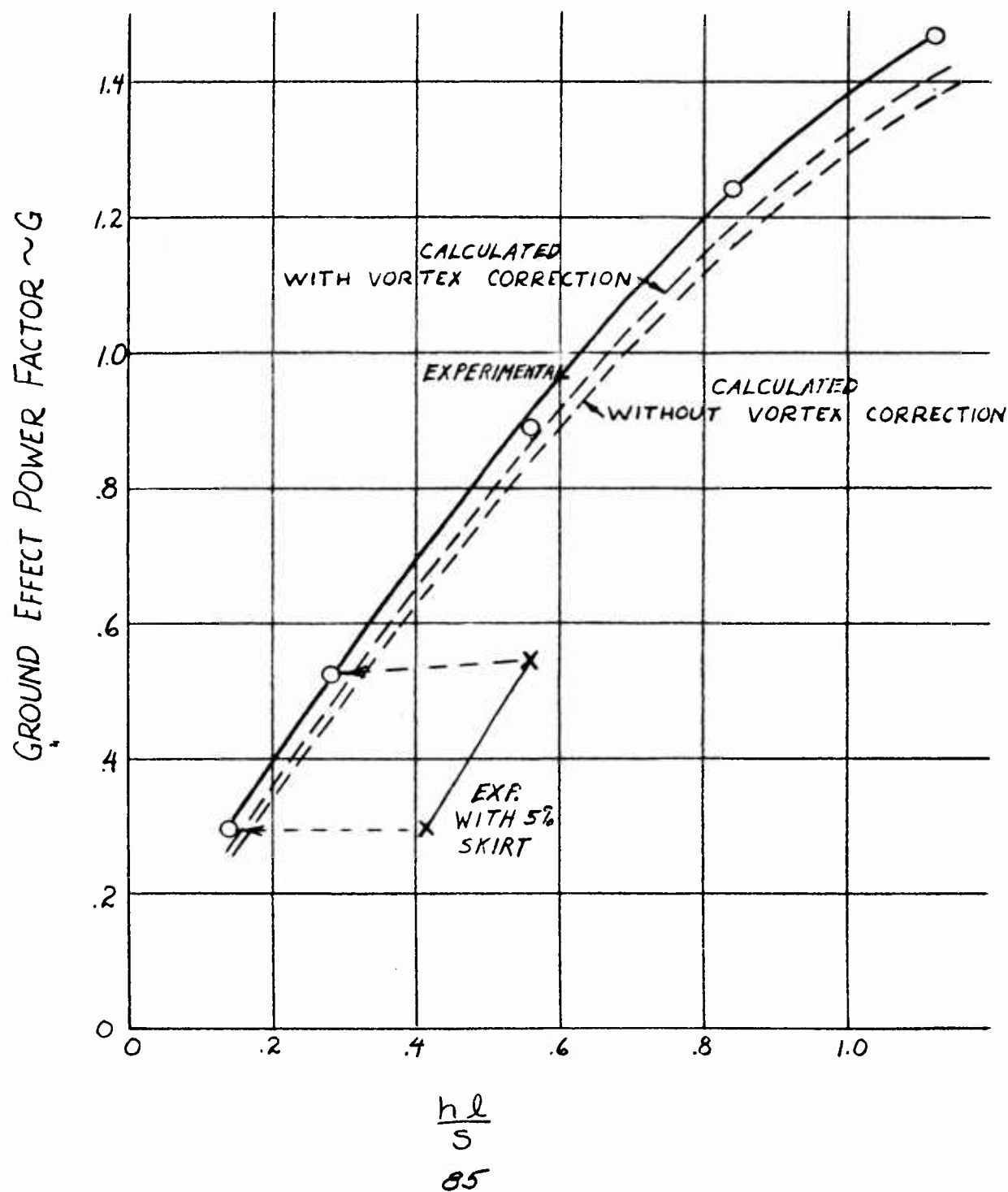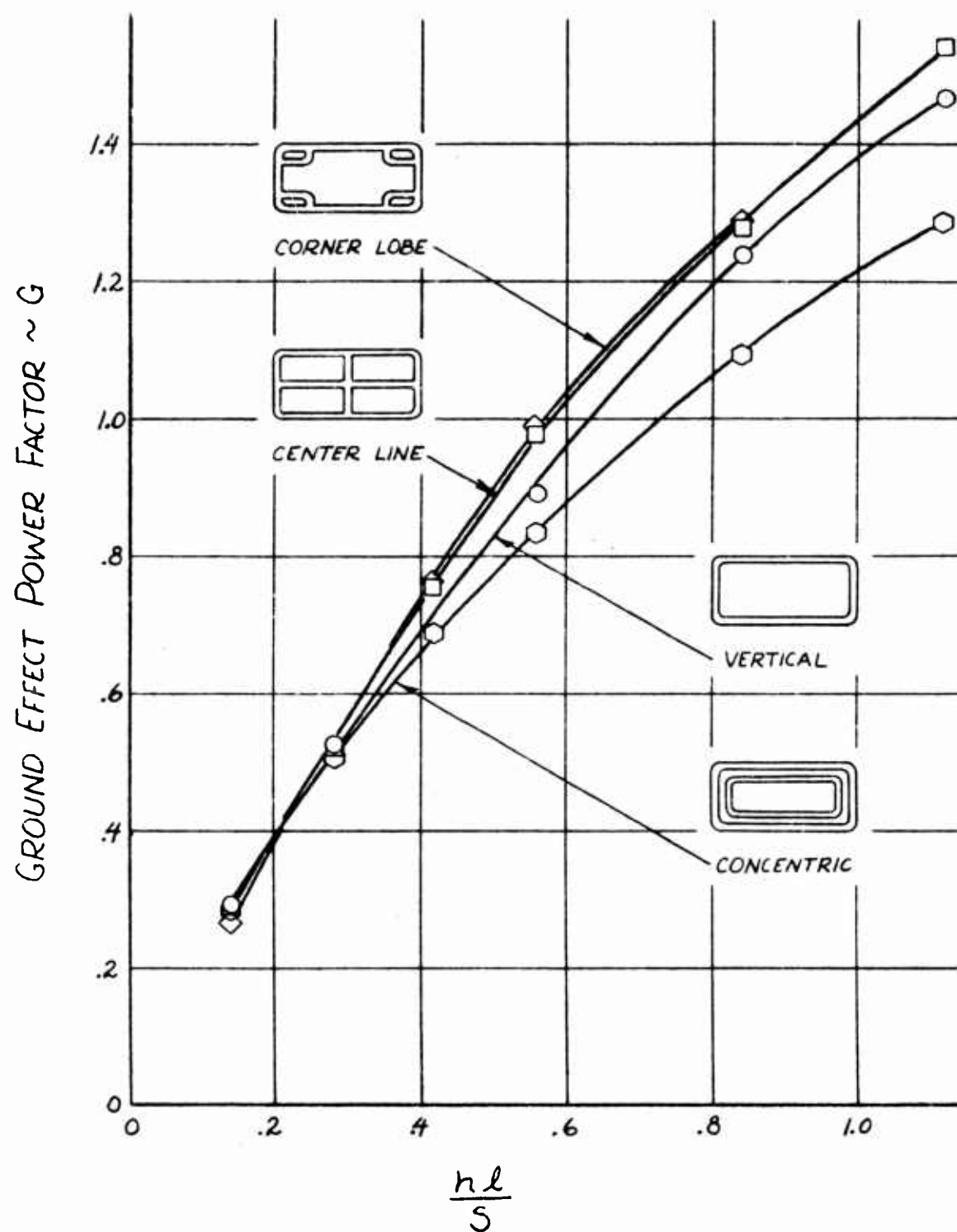
Figure 56

HOVERING PERFORMANCE
VERTICAL PERIPHERAL JET

Figure 57

HOVERING PERFORMANCE
JET SEGMENTED MODELS

CORNER LOBE

CENTER LINE

VERTICAL

CONCENTRIC

GROUND EFFECT POWER FACTOR ~ G

$\dfrac{h\,l}{S}$

Figure 58

STABILITY IMPROVEMENT AND PERFORMANCE COST DUE TO JET SEGMENTATION

	ITEM	PERIPHERAL JET	SEGMENTED JET
	PLANFORM AREA	1.0	1.0
	JET AREA	1.0	1.48
$\dfrac{HEIGHT}{LENGTH} = .10$	$\dfrac{\partial C_m}{\partial \alpha} \sim \dfrac{\% \, C.P. \, SHIFT}{DEG. \, TILT}$	.2 UNSTABLE	-.66 STABLE
	$\dfrac{\partial C_\ell}{\partial \phi} \sim \dfrac{\% \, C.P. \, SHIFT}{DEG. \, TILT}$	.2 UNSTABLE	-.45 STABLE
	$LIFT/JET \, POWER$	1.0	.835
	$(LIFT)^{3/2}/JET \, POWER$	1.0	.915
$\dfrac{HEIGHT}{LENGTH} = .20$	$\dfrac{\partial C_m}{\partial \alpha} \sim \dfrac{\% \, C.P. \, SHIFT}{DEG. \, TILT}$	.25 UNSTABLE	-.17 STABLE
	$\dfrac{\partial C_\ell}{\partial \phi} \sim \dfrac{\% \, C.P. \, SHIFT}{DEG. \, TILT}$	.125 UNSTABLE	-.22 STABLE
	$LIFT/JET \, POWER$	1.0	.856
	$(LIFT)^{3/2}/JET \, POWER$	1.0	.965

ACKNOWLEDGEMENTS

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90

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